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RODNEY D. LAKE

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by

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Lieutenant Commander, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

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IN
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ABSTRACT

The very low frequency band has been characterized by its extremely reliable propagation since the early days of radio. Recent development of oscillators accurate to a few parts in 10^{11} have made it possible to navigate a ship accurately by using existing VLF transmissions. One method of such navigation is discussed. In particular, navigation over long periods of time is explained, with corrections for diurnal phase shift incorporated in the calculation of ships position. Equipment used to obtain experimental data is described and experimental results and sample calculations are presented.

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1. Introduction.

The idea of navigating a ship using very low frequency transmissions is not new. Emissions in the VLF band are particularly appealing for this use because of their reliability and long range. With recent development of highly accurate and stable radio frequency oscillators, VLF navigation has become both possible and practical. For the method of this paper an oscillator is located at the VLF transmitter to phase stabilize the master oscillator. A second oscillator is located on the ship. Both of the oscillators are at the same frequency and the signal received from the VLF transmitter is compared in a phase comparator with the shipboard oscillator. The output of the phase comparator will be constant so long as the ship does not move toward or away from the transmitter site. Any movement of the ship will become apparent however, since the phase of the received signal will shift relative to that of the shipboard oscillator. At the output of a phase comparator calibrated in microseconds, this movement is indicated by a change of 6.18 microseconds for each nautical mile of movement toward or away from the transmitter. The accuracy of this method of determining the movement of the ship depends upon the accuracy of the two oscillators and the stability of the path of propagation. At VLF frequencies the path of propagation is extremely stable and, in general, does not depend upon distance from the transmitter.

If the output of the phase comparator at a known ships

[illegible]

position were noted, a line of present position can be obtained perpendicular to the propagation path by finding the microseconds change. If two or more VLF stations are monitored, a fix on the position of the ship can be found at the intersection of these lines of position. Accuracies of less than a mile are possible.

As might be expected there are many chances for error in this procedure. In many cases these errors can be predicted and compensated for. In others they can be recognized and the signal that is in error discarded for navigational purposes until it is once again free of error.

In the past few years considerable research has been done in the area of VLF propagation. Much of this research applies directly to the VLF navigation problem; specifically to the prediction of changes in the propagation path. The results of some of this research, as it applies to ship navigation will be presented in this paper.

Blackband[7] and Stanbrough[23] have used this method of navigation experimentally for various periods of time with good accuracy. This paper relies heavily on their work and that of others.

2. The Waveguide Mode Theory of VLF Propagation.

Propagation of radio waves at VLF frequencies is characterized in general by long ranges with stable levels at the receiver. Considerable effort has been expended in recent years to determine the mechanics of this propagation. The mathematics involved in explaining this have been found to be most complex. This complexity is primarily caused by the curvature of the earth and the non-homogeneous character of the reflecting surfaces of the earth and ionosphere. Many papers have been presented that take these factors into consideration[2][8]. In these papers the volume between the surface of the earth and the ionosphere is considered to act as a waveguide at very low frequencies. Some of the apparent inconsistencies of propagation at VLF are most easily explained by this waveguide theory. Values of phase variations and signal intensity at various distances calculated using the waveguide model agree very closely with experimental observation[10][4]. No attempt will be made in this paper to justify the waveguide mode theory of VLF propagation. Many of the books and papers listed in the Bibliography contain considerable mathematical development related to the theory. The waveguide mode theory explains the characteristics of VLF propagation that are of particular importance in the prediction of phase changes at the receiver. The predictions of phase changes are of great importance in VLF navigation, and in this regard the results of the waveguide mode theory will be used.

3. The Diurnal Phase Change.

One of the primary characteristics noted in VLF propagation studies is that of the diurnal phase change. The propagation path between transmitter and receiver is extremely stable while the entire path is in daylight. The path for a night time propagation path is considerably less stable, and in addition is characterized by a phase shift from the daylight path. The magnitude of this phase change depends upon the distance between the transmitter and the receiver. An idealized example of a 24 hour plot of the phase at a receiver is shown in Figure 1 (a). This shows an east to west transmission path, that is the receiver is west of the transmitter. E to A indicates the phase at the receiver during a period when the entire propagation path is in daylight. Point A represents sunset at the transmitter site. The phase changes linearly until B which represents sunset at the receiver site. Line B-C represents the phase of the received signal during the time the propagation path is in darkness. Point C represents sunrise at the transmitter and the phase changes to point D which is the time of sunrise at the receiver. The phase of the received signal is now identified with its previous value and maintains its daylight value to Point E. During the next 24 hour period the pattern will repeat. Figure 1 (b) shows one of the many variations in this pattern. In this case the location of the transmitter is north and east of the receiver so that sunset arrives at both points simultaneously.

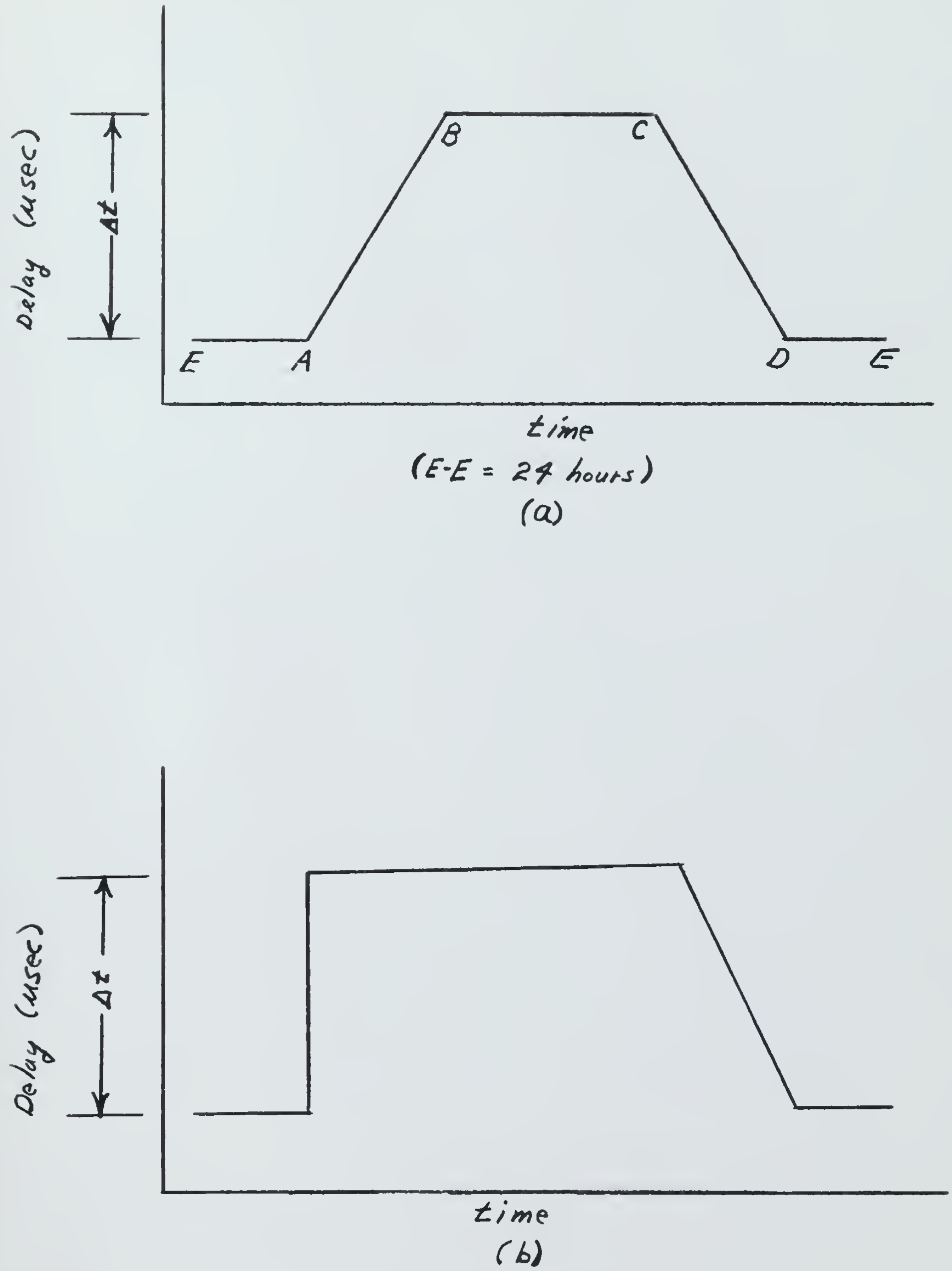


FIG. 1. DIURNAL VARIATION PATTERNS

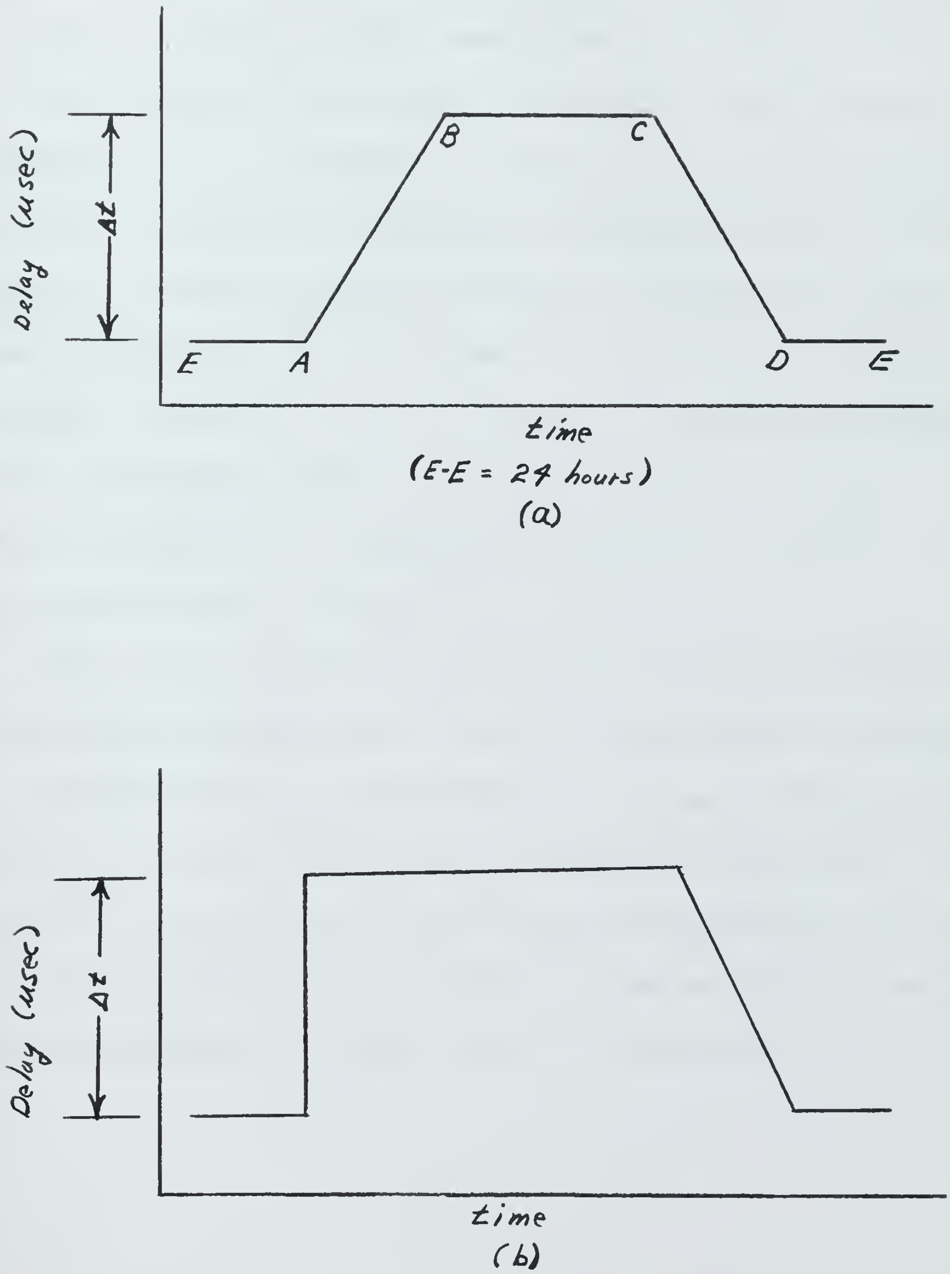


FIG. 1. DIURNAL VARIATION PATTERNS

The diurnal shift can be explained by the waveguide theory. During the day, the action of sunlight forms an ionized layer at an altitude of about 70 kilometers. During daylight the walls of the waveguide are formed by this layer and the surface of the earth. At night this ionized layer disappears and the nighttime reflecting surface appears at an altitude of about 90 kilometers. When the walls of the waveguide are brought closer together, the phase velocity of the waves propagating in the guide is increased. Consequently the phase velocity of the VLF waves is greater through a daylight propagation path. It is convenient to refer to the change in phase as a change in transmission time. This is indicated as Δt in Figure 1.

When VLF transmissions are used for ship navigation, these diurnal phase shifts must be anticipated and their time of occurence must be predicted so that measurements taken during the diurnal shift may be properly processed. If it is desired to use both day and night transmissions for navigation, the pattern and magnitude of the shift must be predicted in addition to the times of occurrence.

4. Prediction of the Diurnal Change.

For purposes of prediction of the diurnal phase change, the great circle path around the earth may be divided into three general zones of similar propagation conditions. These are shown in Figure 2 and can be named:

Zone I - The multi-mode zone

Zone II - The single mode zone

Zone III - The multi-path zone

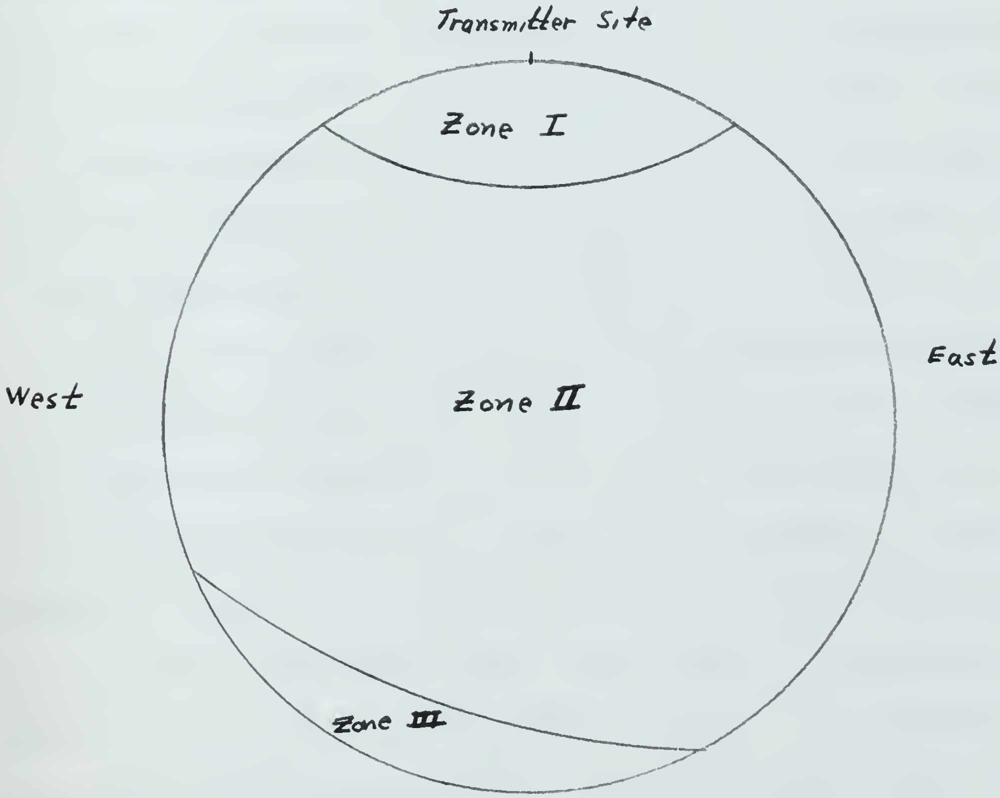


Figure 2. Zones of similar propagation conditions

4a. The Multi-Mode Zone.

The height of the earth-ionosphere waveguide is about 2 to 9 wavelengths long in the frequency range 10 to 30 kilocycles. Because of this, many modes of high order can be propagated. These high order modes are attenuated more rapidly than the first-order mode however, and they become small relative to the first-order mode. The distance where they may be neglected depends upon the height of the ionosphere reflecting surface and upon the frequency of transmission, but it is generally considered to be in the neighborhood of 4000 kilometers[18]. Within this zone the modes interact in a complex manner and the phase of the received signal may vary in a similarly complex manner[13]. The use of VLF emissions within the multi-mode region for navigation of a moving ship does not seem promising at the present time because of this interaction between modes. Sufficient VLF signals are available from outside any particular zone however, so this is not considered to be a great disadvantage. It is also possible that further research on propagation within the multi-mode region will allow some parts to be used. Caution must be observed when using VLF signal for navigation. If the ships track passes within the multi-mode zone specified for the VLF transmitter, the signals received will not be usable for navigation in the same manner as those outside the zone.

4b. The Single Mode Zone.

Beyond the multi-mode zone the higher order modes are no longer of sufficient magnitude, and only the first-order mode need be considered. The single mode region extends throughout both zones II and III in Figure 2. This region is characterized by VLF propagation that is normally stable with a predictable diurnal phase shift. This diurnal shift depends upon the frequency and the distance from the transmitter to the receiver. Wait[10] gives an arithmetical expression for $\Delta t/D$, derived from the mode theory:

$$\Delta t = \frac{D}{0.3}\left(\frac{c}{v_n} - \frac{c}{v_d}\right) \text{ microseconds}$$

where D is the distance to the transmitter

vn and vd are the night and day phase velocities respectively.

c is the speed of light in space.

A value of phase velocity at the frequency of interest can be calculated using the mode theory, and Wait[8] has published some charts of calculated phase velocities vs. frequency for various reflecting surface heights. Figure 3 is a plot of these calculated values for a perfectly conducting ground and imperfectly conducting ionosphere. This is a close approximation to propagation over sea water. Measurements of the phase velocity of VLF propagation have been experimentally measured[22] at a frequency of 18 kc and v_d/c and v_n/c were found to be 0.998 and 0.995 respectively. These are very close to Wait's calculated values for h=72 kilometers during daytime and h=96 kilometers during the night. In the single

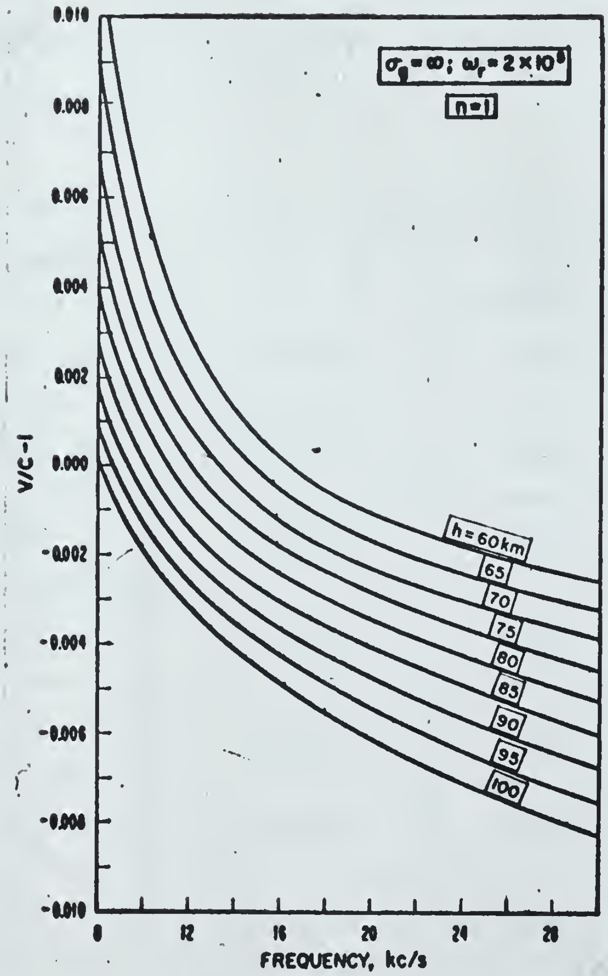


FIG. 3. PHASE VELOCITY OF THE FIRST MODE FOR A PERFECTLY CONDUCTING EARTH AND AN IMPERFECTLY CONDUCTING IONOSPHERE (FROM WAIT)

mode zone the diurnal phase shift increases nearly linearly with distance, and the magnitude of the shift can be calculated from $\Delta t = D^{k_v}$ where D is the distance from the transmitter and k_v is a constant that will depend upon the frequency. Table I gives values of k_v for some frequencies of interest, where h_d=72 and h_n=96, kilometers. These are calculated from Figure 3.

Frequency	$\frac{c}{v_n} - \frac{c}{v_d}$	kv ($\times 10^3$)
16.0	0.00231	7.70
17.8	0.00232	7.74
18.6	0.00247	7.90
20.0	0.00241	8.05
21.4	0.00242	8.06
24.0	0.00262	8.74
26.1	0.00258	8.60

TABLE I

k_v for h_d=72 and h_n=96 Kilometers

Blackband has determined experimentally(18) and Wait has verified mathematically(10) the form of the variation of Δt vs. D. Figure 4 is a plot of Blackband's experimental data at 16 kc. Blackband has chosen a linearizing factor, k_f, to

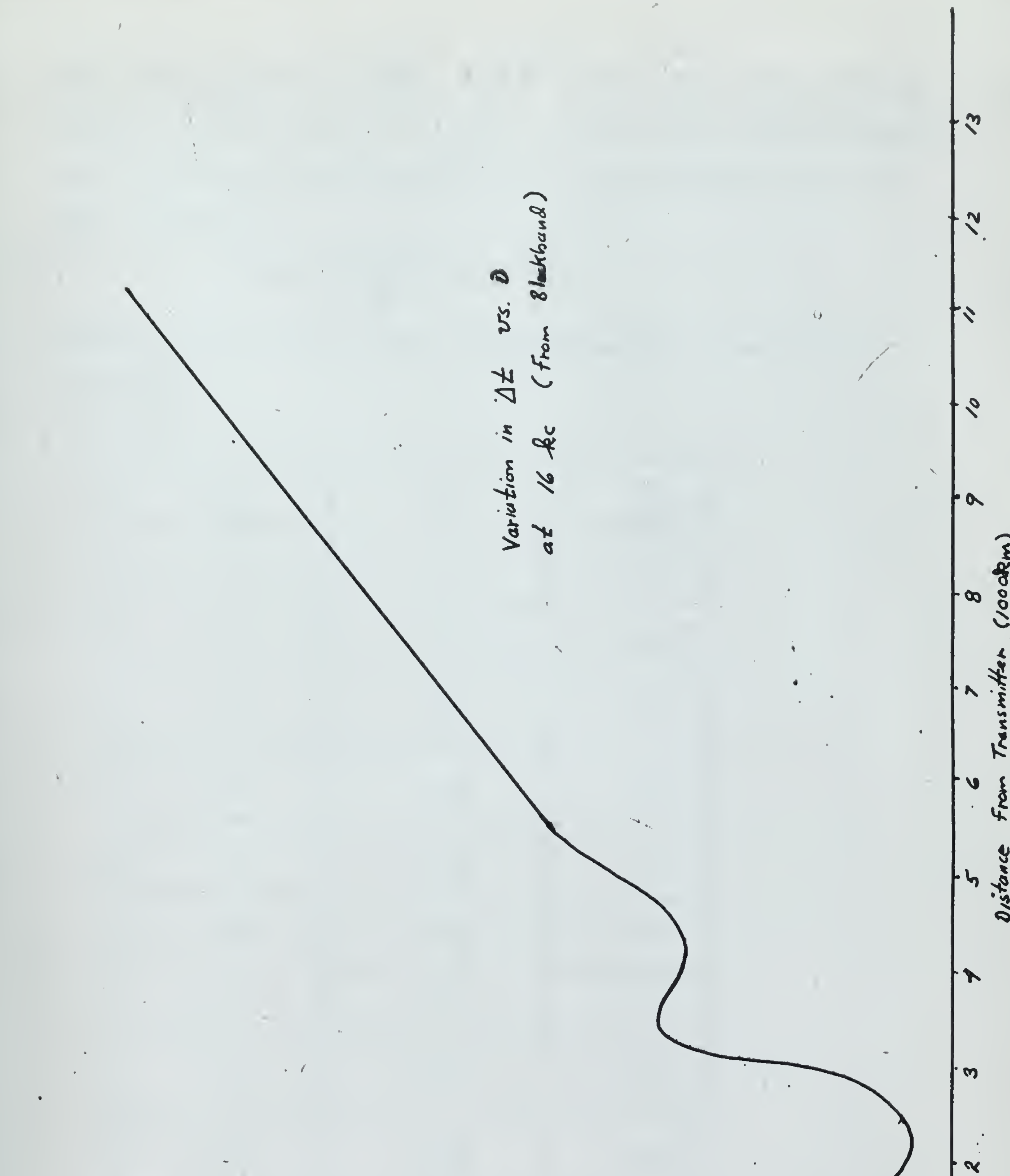


FIG. 4. Δ t VS, D AT 16 KCS.

show the variation of $\frac{\Delta t}{D}$. Wait[10] has found values for k_f mathematically from mode theory. These values agree closely with Blackbands' experimental k_f. k_v is related to k_f by the relation:

$$k_v = \left\{ \frac{7.87}{k_f} \right\} \times 10^{-3}$$

Table II gives values of k_v found from Wait's calculated values of k_f.

f (kc)	k_f	k_v $(\times 10^3)$
10	0.7	11.25
12	0.9	8.75
14	1.0	7.87
16	1.08	7.28
18	1.09	7.22
18.6	1.08	7.28
20	1.07	7.35
21.4	1.03	7.65
24.0	0.96	8.20
26.1	0.92	8.55

TABLE II

Values of k_v Calculated from k_f

The values of k_v in Table II seem to be closer to those obtained experimentally. Unfortunately there are few data published of measured values of Δt above 18 kc. Most data from experimental measurements seem to be for frequencies of 16 and 18 kc. Even here, large discrepancies for k_v appear. Tables III and IV compare the values of k_v obtained at these frequencies at various distances. The data is from Blackband[18]. Researchers at the ROYAL AIRCRAFT ESTABLISHMENT (FARNBOROUGH) have analyzed these and other data to determine if there is any predictable effect on Δt caused by latitude or direction of path. No such effect has been found, and Δt appears to be independent of these factors. Until more data is accumulated on the variation of Δt with frequency, it appears that an accurate prediction of the diurnal phase shift at a random location is not yet possible.

At a particular location however, the diurnal phase shift is remarkably constant from day to day. Figures 5, 6, and 7 are diurnal phase shift patterns of NBA, NSS and NPM recorded at Monterey, California over several days. These have been corrected for frequency drift. Figure 8 is an example of an uncorrected pattern. These are typical of the patterns recorded, and the pattern of each set is clear. Times of sunrise and sunset can easily be seen on the figures. These constant and predictable patterns of day to day diurnal shifts have been noted by a number of researchers.

Some of the values of Δt measured at Monterey, California are shown in Table V, and compared here with the values

that are predicted from the value of k_v from Table II.

D (km)	Δt (μ sec)	k_v ($x10^3$)
5174	34.5	6.66
5778	43	7.45
6947	50	7.20
7424	48	6.47
10901	72	6.60

TABLE III

Measured Values of k_v at 16 kcs

D (km)	Δt (μ sec)	k_v ($x10^3$)
4297	29	6.91
4670	27	5.8
8462	66	5.7
8675	70	6.07
9087	75	6.80
9795	71	6.95

TABLE IV

Measured Values of k_v at 18 kcs

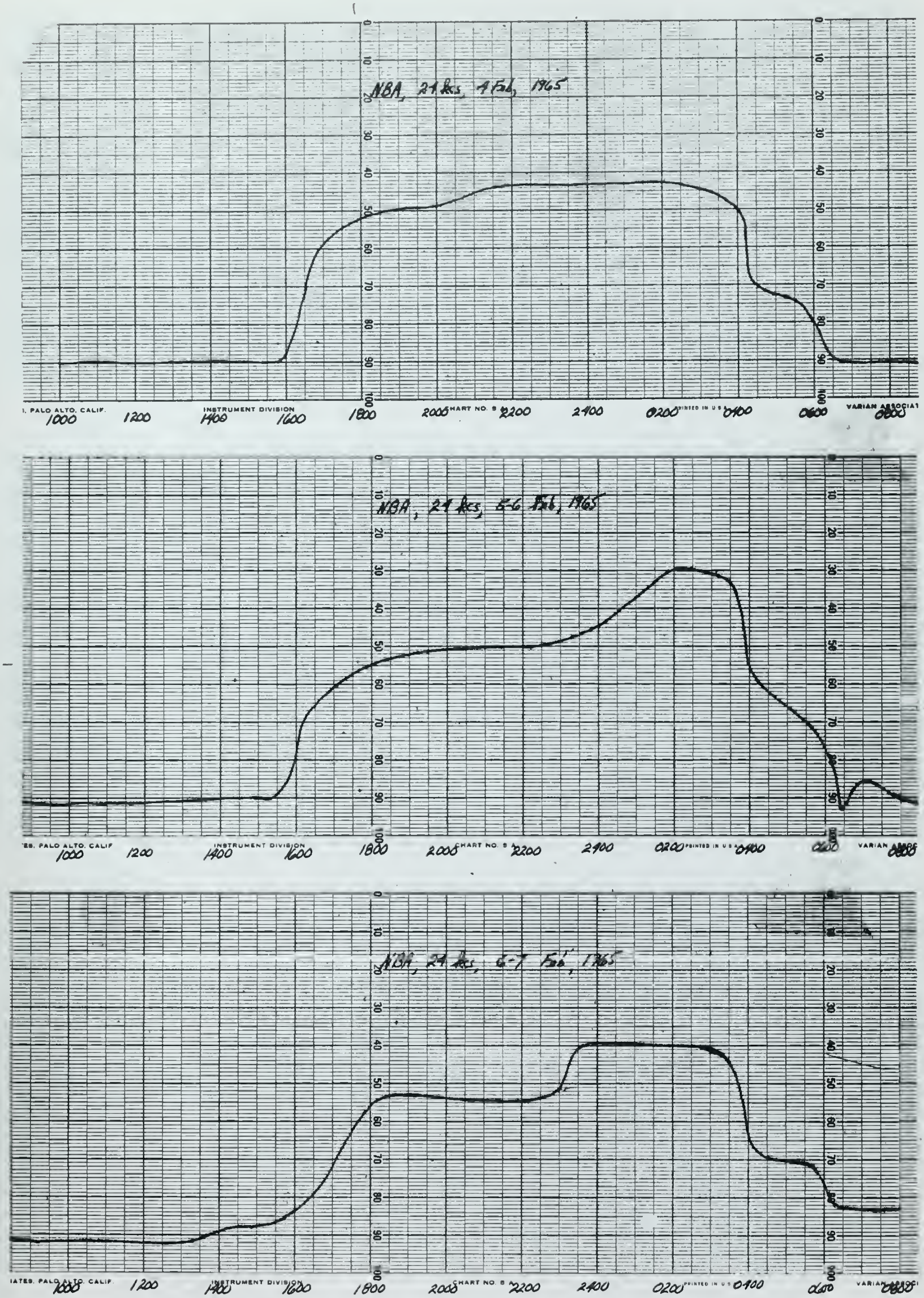


FIG. 5. VARIATION OF PHASE OF NBA (24.0KCS) AT MONTEREY

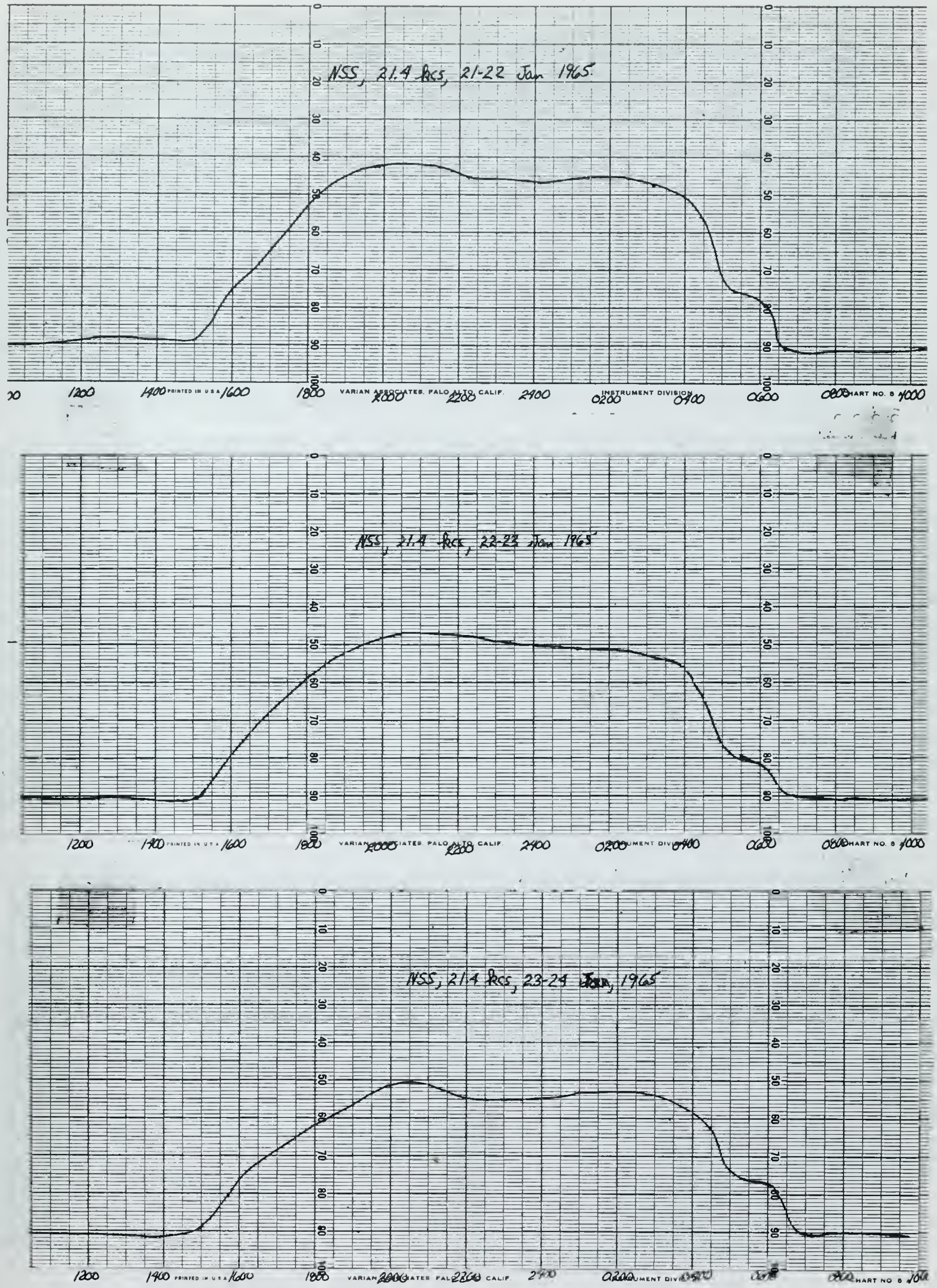


FIG. 6. VARIATION OF PHASE OF [illegible] AT MONTEREY

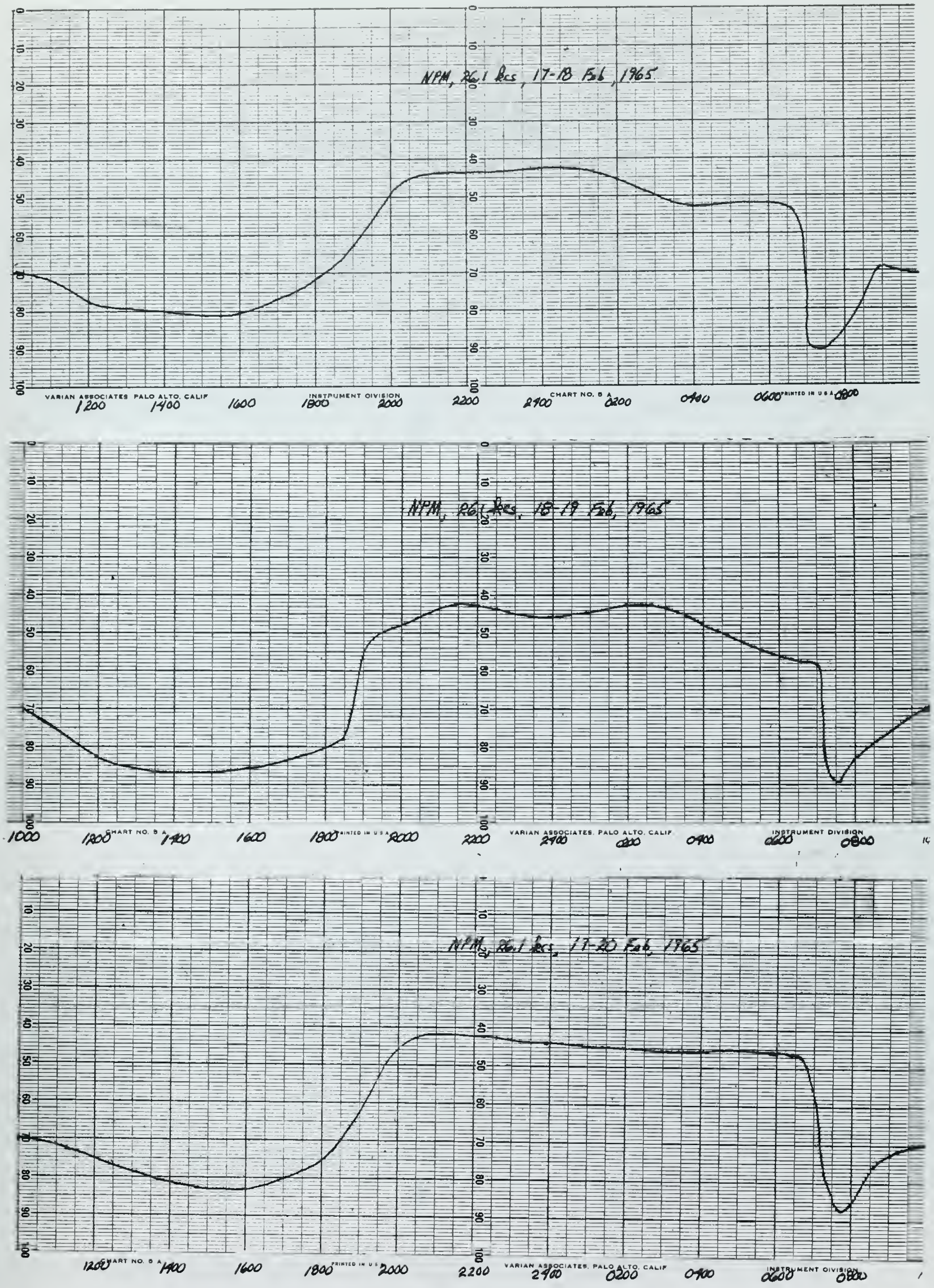


FIG. 7. VARIATION OF PHASE OF NPM (26.1KCS) AT MONTEREY

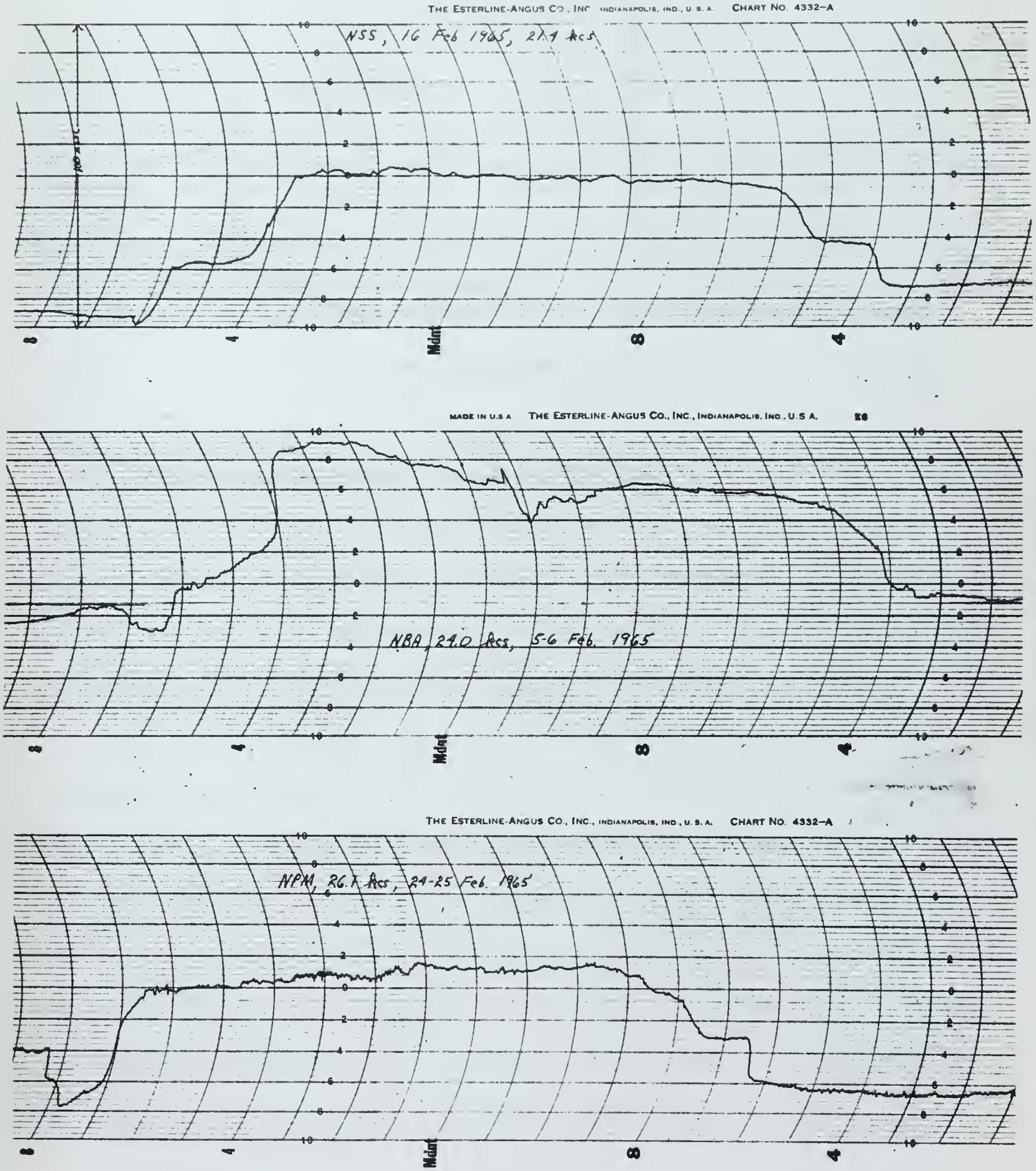


FIG. 8. SOME UNCORRECTED VARIATIONS OF PHASE

Station	Frequency (kc)	Distance (km)	Measured Δt	Computed Δt
GBR	16	8591	52	62.5
NSS	21.4	3970	40	30
NBA	24	5242	42	43
NPM	26.1	3863	43	33

TABLE V
Comparison of Some Values of Δ t Measured at Monterey With the Computed Values

The measured values of Δ t for both NSS and NPM are both about 130 percent of the computed value. In these cases it may be that the distance is not sufficient for the higher order modes to be attenuated sufficiently, and Monterey may be within the interference region for these stations.

Once the diurnal pattern for an area is found, this pattern can be used to correct the microseconds readings for that area. The pattern must be modified as the times of sunset and sunrise change, and possibly slight modifications in Δt will be necessary as the seasons change. A single pattern may be used in an area of several hundred square miles, and slight modifications of Δ t with distance are possible to extend a pattern to adjacent areas.

4c. The Multi-Path Zone.

Zone III in Figure 2 is a region where particular care must be taken when using a VLF signal for navigation. This is because of the possibility of receiving and tracking a signal around the longer great-circle path. The VLF signal around the long great circle path is always present of course. By using time sharing and directional antennas, Westfall[21] in San Diego has measured and compared phase and amplitude of the signal transmitted from NAA over complimentary great circle paths. Normally however, the signal received over the shorter path is the greater in amplitude and overrides the weaker signal. In Zone III, the long path may be the preferred path for various reasons.

It has been shown[17][16] that VLF waves are attenuated less when traveling from West to East. Because of this the two path region is tilted as shown in Figure 1. In addition, the boundary is not symmetrical, and depends somewhat on latitude, the differences in attenuation being largest for an equatorial path[3].

Another factor to be considered is the difference in phase velocities between nighttime and daylight paths. Since the phase velocity of the daylight path is greater, this path would be preferred over the night path.

Measurements have been made of the NPM signal received at Singapore[14] over a period of two years. The diurnal variation shows a double-humped pattern that is the result of splitting the propagation path into approximately two 12-

hour periods. This indicates that, in this case, the long path of 29,000 kilometers is preferred over the short path of 11,000 kilometers during the daylight.

The usefulness of VLF signals in Zone III for navigational purposes is marginal at the present time, since the use of directional antennas on ships is impractical. Singapore-NPM readings did exhibit a regular pattern however, and it may be that the propagation path may be predictable and consequently a signal received in Zone III usable for navigation over long periods of time. Further data appears necessary to determine this, and also to determine the boundaries of Zone III for each VLF transmitter.

5. Seasonal Variations of the Diurnal Phase Change.

An obvious variation of the diurnal phase change with the season of the year is that change associated with the length of the day. During the summer the daylight path is of considerably longer duration than the daylight path in the winter.

Observation of the phase variations over various paths indicate there are probably small variations of the diurnal shift with the change in season[3], particularly for paths that pass near the polar regions. The height of the ionosphere appears to change with the seasons causing a change in phase velocity. Researchers in Paris, France have measured the diurnal shift of NBA on 18 kcs over a period of three years. They have noted Δt to be 70 μsec at the winter solstice, 80 μsec at the summer solstice and 75 μsec at the equinoxes[16]. As information on the shift in phase velocity with the change in seasons becomes available, a small correction for this obtained from published tables can be included in the calculations of the line of position.

A second and even smaller variation may be caused by changes through the eleven year sunspot cycle. Sufficient information is not available on this point, but a correction for this can also be easily made from tabulated values.

6. Anomalies of Propagation.

There are several events that may disrupt the path of propagation at very low frequencies. These events will consequently cause errors, possibly of large magnitude, in the VLF navigation system. The events are called sudden ionospheric disturbances (SID). There are three major causes of a SID. These are solar flares, magnetic storms and high altitude nuclear bursts. The effects of all of these are similar in that they perturb the ionosphere and cause unpredictable discontinuities of the phase of the VLF signal received. The length of this perturbation may be from a few hours for a solar flare to a few days for a magnetic storm. During high altitude atomic tests, some paths have been disturbed as much as twelve days, with the height of the ionosphere decreased by as much as 5 km from its normal altitude(15). It is not necessary that the disturbance occur directly along the path of propagation because of the waveguide nature of the propagation involved(19).

During these periods of disturbance, VLF signals are unusable for navigation, although they are still usable for communications. When such a disturbance occurs, ships using such a VLF navigation system must be immediately notified of the disturbance and notified once again when the ionosphere has returned to normal.

The frequency of occurrence of solar-caused sudden ionospheric disturbances of sufficient intensity to cause phase errors in VLF transmissions does not appear to be known.

They will occur most frequently during periods of high solar activity. In general it seems they will occur infrequently and will not be a major source of error to the navigation system.

7. The Frequency Standard.

The frequency standard is the heart of the VLF navigation system, and it is only with recent development of highly accurate frequency standards that such a system has become possible. The standard used should be of high quality and in any case should have a long term stability of at least a few parts in 10^{-10}. At the U. S. Naval Postgraduate School a VARIAN type V-4700 Rubidium Frequency Standard was used, and a standard of this type seems well suited for shipboard use. This particular standard is specified to maintain a long term stability of 5×10^{-11} in a one year period (standard deviation).

Whatever frequency standard is used, the initial procedures to ready it for use are similar. Before the standard can be used for navigation it must be energized for a sufficient period of time for it to stabilize. This may be a few months for a crystal oscillator standard or only a few days for a standard utilizing an atomic resonance stabilization similar to the Rubidium Vapor standard.

A short failure of the power supplied to the frequency standard will nullify the previous data obtained and will require that a new ships position be obtained by other means. A failure of sufficient duration to allow the ovens to cool will cause instability, and the standard will not be usable until it has been energized a sufficient time for it to stabilize once again. Because of this, it is standard practice to supply the frequency standard from a wet battery

supply and to constantly charge these batteries from the local source of power. In the event of a power failure, the batteries supply full power to the standard until the main supply is restored.

Once installed on a ship, the frequency standard is useful for other purposes. Radio transmitters or receivers can obtain their frequencies from a frequency synthesizer energized from the ships frequency standard. As an example of the accuracy possible, a transmitter and receiver could be set at 20 megacycles and would be as accurate as 20,000,000.00 cycles per second, $\pm$ 0.001 cycle. Electric clocks can be powered by a source excited by the frequency standard. Once the clocks are set they would gain or lose about 10 microseconds a day, or a second every 300 years.

8. The Tracking Receiver.

The second unit used for obtaining the VLF navigation fix is the tracking receiver. This is a special VLF receiver that measures the phase difference between the local oscillator and the signal received. At the U. S. Naval Postgraduate School a TRACOR model 599G VLF receiver was used. This receiver was developed for the purpose of utilizing the frequency stabilized VLF stations for frequency calibration, and it is particularly adaptable for use in the VLF navigation problem. A useful feature of this receiver is the digital dial on the front panel that displays continuously the relative time difference between the local frequency standard and the incoming signal, recording changes in phase as small as 0.1 microseconds. Outputs are also available to record phase difference on an external chart. The tracking receiver also electronically phase shifts the reference signal within the receiver so it is phase locked to the incoming signal. Figure 9 is a simplified block diagram of a tracking receiver. Since the receiver bandwidth is narrowed by the phase tracking servo, extremely high sensitivity is possible. The TRACOR receiver is rated at a sensitivity of 0.01 microvolt and will phase track with an input signal to noise ratio of -50db.

NPM and NAA present special problems during the periods they transmit with frequency shift keying. It is possible to track a VLF station utilizing FSK if one side of the keying signal is locked to the frequency stabilized carrier.

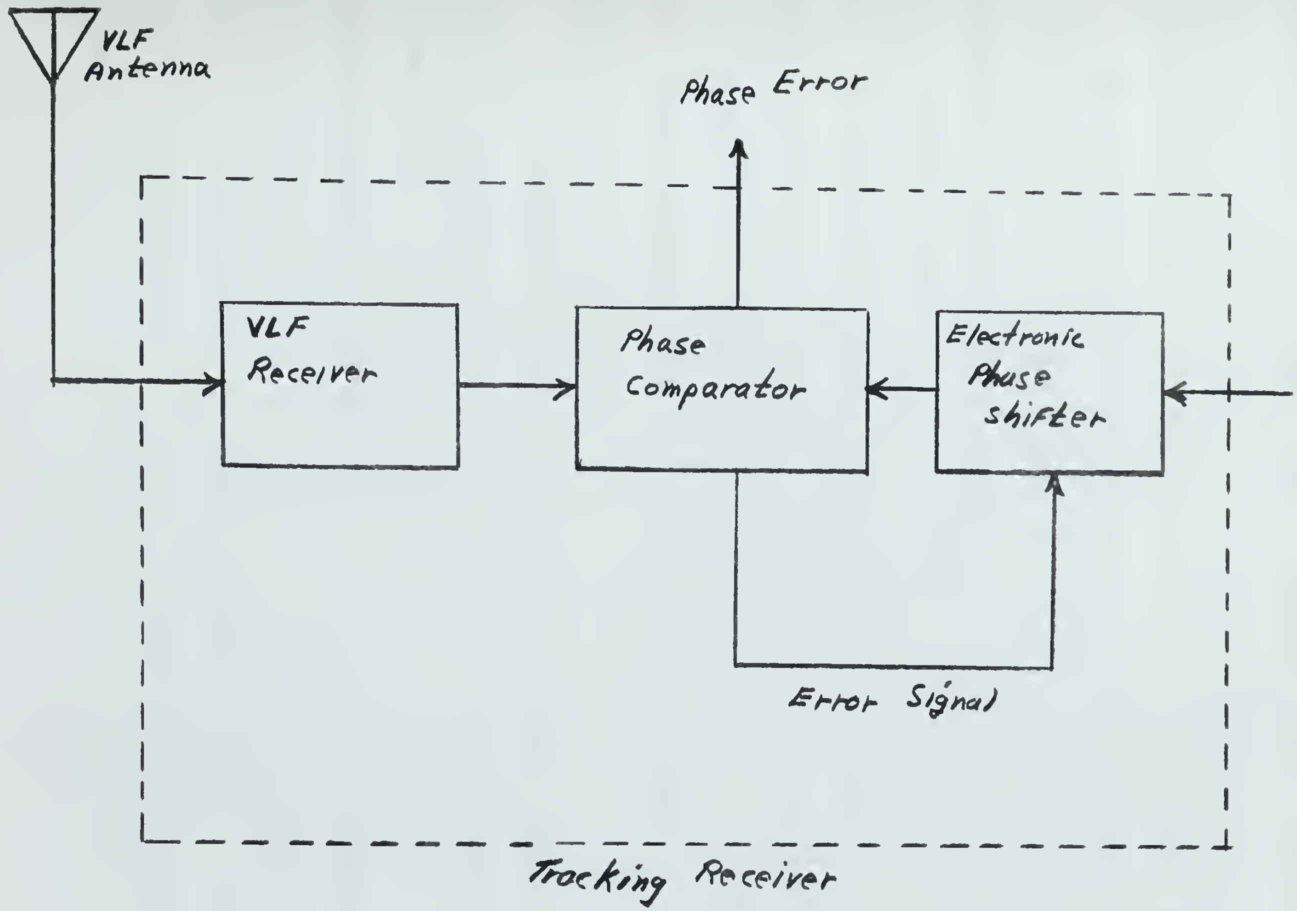
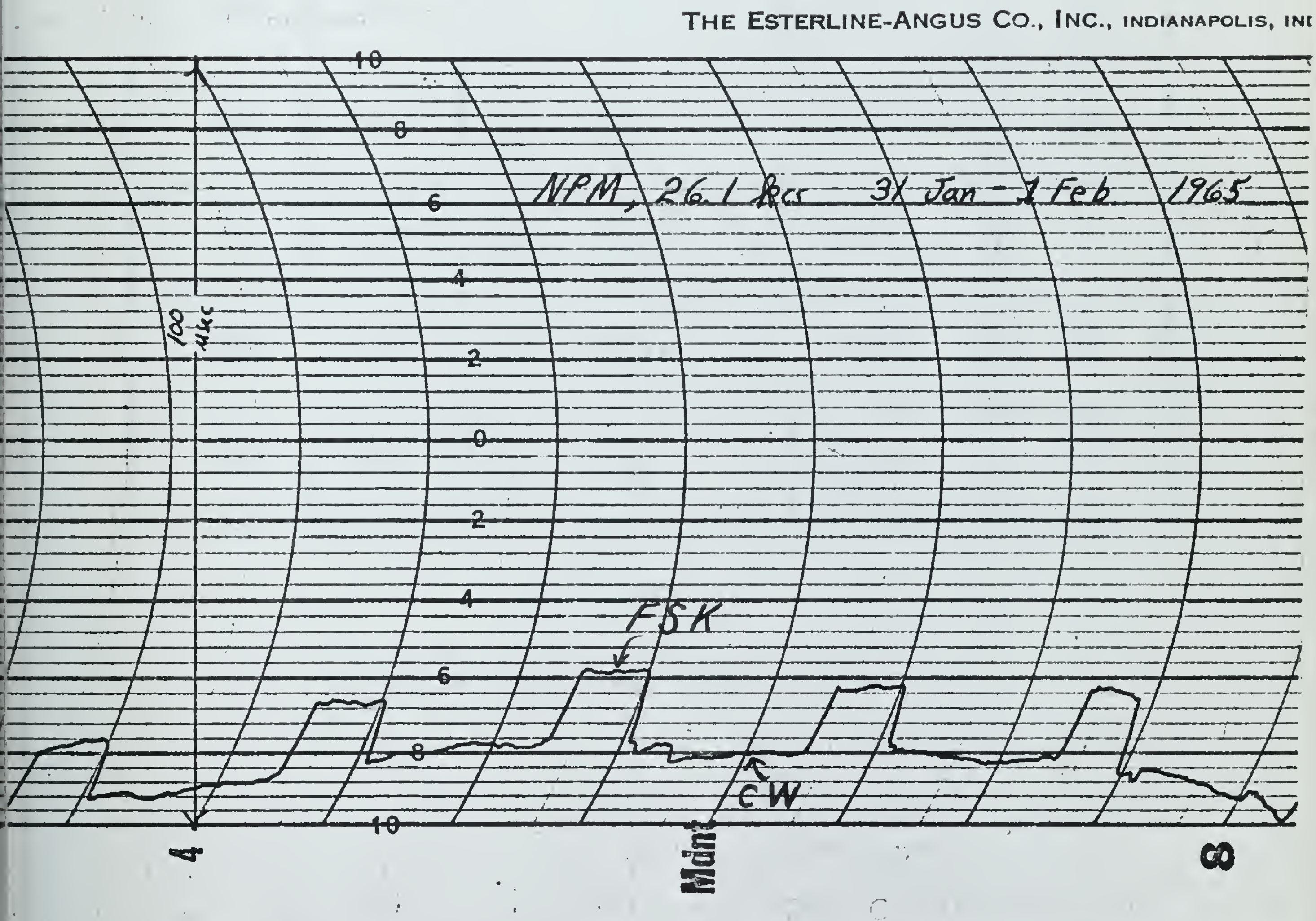


FIG. 9. BLOCK DIAGRAM OF A TRACKING RECEIVER

Experience at the U. S. Naval Postgraduate School indicated that NPM could be tracked during the FSK transmissions and that NAA could not be tracked during FSK. Figure 10 is a portion of a chart of NPM received at the U. S. Naval Postgraduate School. NPM was transmitting with frequency keying for one half hour commencing every odd hour (Monterey time). The FSK circuitry caused an offset of about 10 microseconds but the signal was tracked and could be used for navigation.

It will be necessary to have a receiver for each station tracked for VLF navigation. A single frequency standard is sufficient for all the receivers. Normally the output of each receiver will be plotted on a recorder, and this record will indicate the microseconds change in phase as the ship moves relative to the VLF transmitter. The microseconds dial on the receiver front panel will also indicate this change. The chart will be useful to indicate the onset of the diurnal phase change however.

A tracking receiver will give a phase error that may be used for navigation from any frequency stabilized VLF CW transmission. The long time constant used will completely smooth out any CW keying the station may be using. The transmissions of most of the VLF stations presently transmitting can therefore be used without change. Table VI lists the VLF stations that are now frequency stabilized. The frequencies of the Navy transmitters are subject to change.



- FIG. 10. A PHASE PLOT OF NPM (26.1KCS) WHILE TRANSMITTING BOTH CW AND FSK

Station	Freq. (kc)	Location (Lat. & Long.)	Sponsor	Type of Keying
WWVL	20.0	(40 40'55.9"W) (105 02'53.9"W)	National Bureau of Stand.	CW
NBA	24.0	(9 04'30"N) (79 34'30"N)	USN	CW
NPM	26.1	(21 25'N) (158 90'W)	USN	CW FSK
NAA	17.8	(44 39'N) (67 17'W)	USN	CW FSK
NLK	18.6	(48 12'N) (121 55'W)	USN	CW
NSS	21.4	(38 59'N) (76 27'W)	USN	CW
GBR	16.0	(52 22'N) (1 11'W)	British Post Office	CW

TABLE VI

Frequency-Stabilized VLF Stations

9. Determining Oscillator Drift Rates.

After the shipboard oscillator has stabilized, the rate of drift between this oscillator and the master oscillators at the various transmitters must be determined. This rate of drift will vary from station to station, but should be steady and predictable. It is this feature of a small, predictable drift between oscillators that allows stabilized VLF transmissions to be used for navigation.

Pierce was the first to discover that oscillators could be compared with high precision through the use of very low frequency transmissions(3). This has become a standard procedure throughout the world, with WWVL, NBA and GBR providing carriers of high frequency stability for scientific use.

The procedure for obtaining these drift rates is not complex, but because of the small errors involved, long intervals of measurement are necessary. A 24 hour measurement interval is recommended, since propagation conditions between receiver and transmitter recur at 24 hour intervals. In addition a daylight propagation path is preferred because of the more stable conditions. Figures 11, 12, 13, and 14 are typical plots of drift rates. These were obtained at the U. S. Naval Postgraduate School. A tracking receiver with a direct reading microseconds dial is recommended for this purpose, although the same data can be obtained using a chart recorder. At 24 hour intervals the change in the output of the phase comparator is noted. Since this output is calibrated in microseconds it can be used directly in computa-

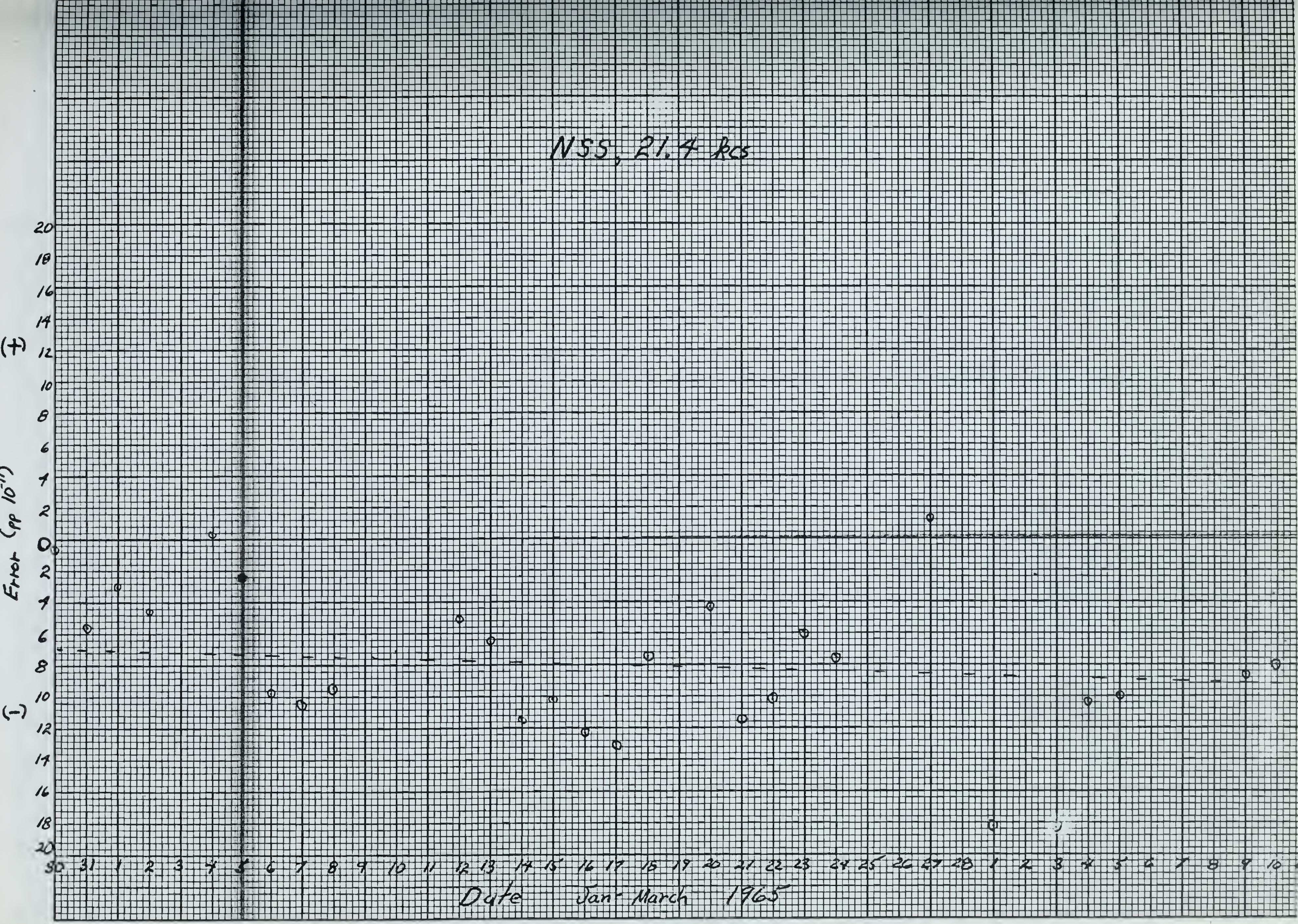


FIG. 11. DRIFT RATE, NSS, JAN. - MARCH 1965

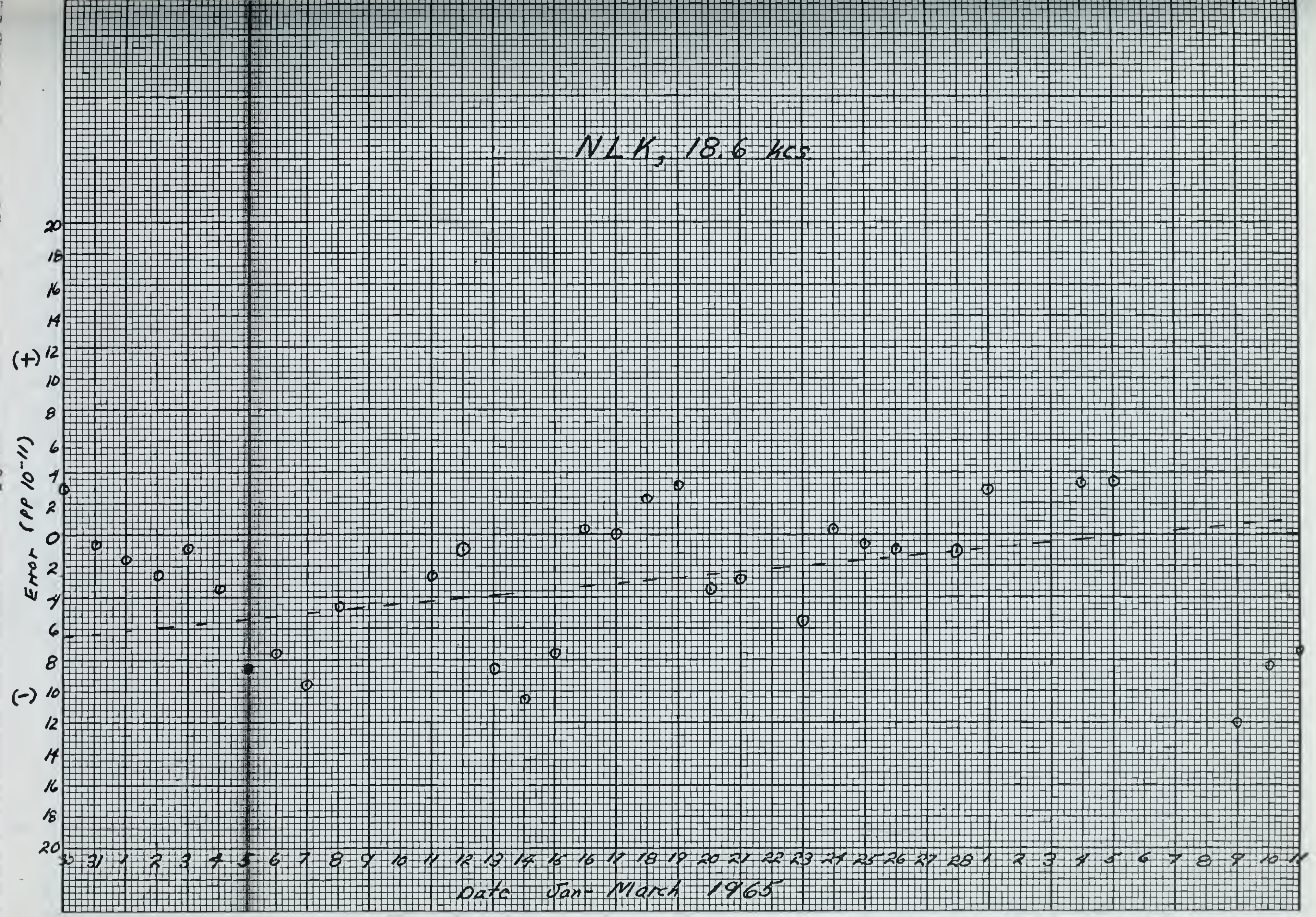
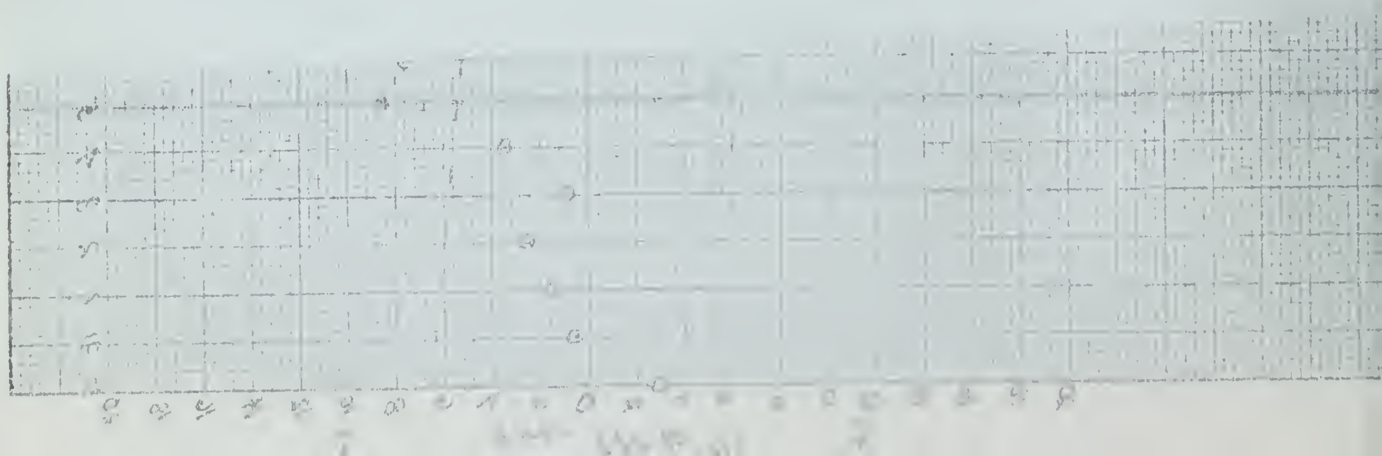


FIG. 12. DRIFT RATE, NLK, JAN. - MARCH 1965



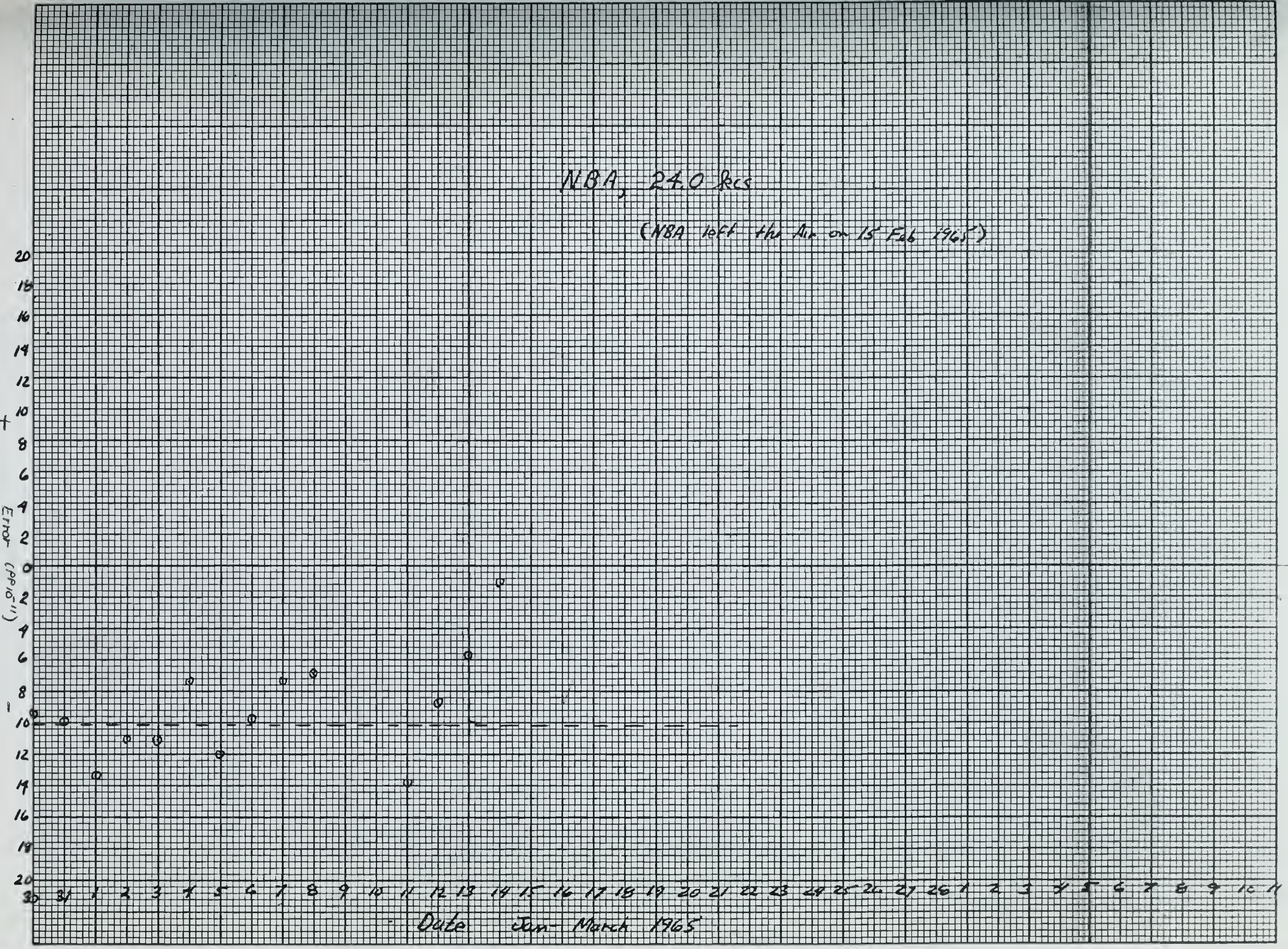


FIG. 13 DRIFT RATE NBA JAN. - FEB. 1965

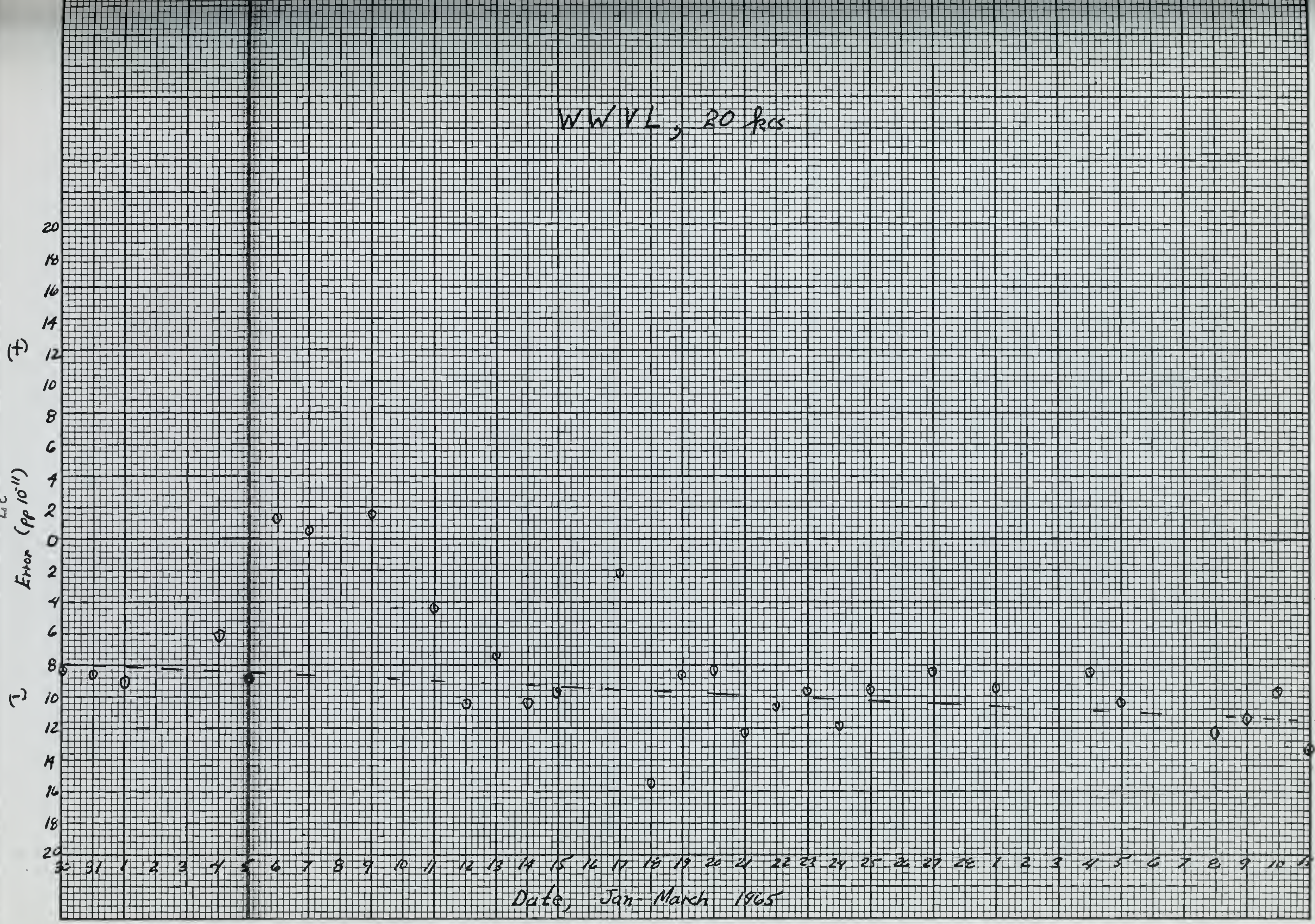


FIG. 14. DRIFT RATE, WWVL, JAN. - MARCH 1965

tions. For a period of time T, the error is:

$$\text{error} = \frac{\Delta t}{(T)\ (0.36)}$$

where Δt is the microseconds change during T. When several day have been plotted, the rate of drift should begin to be apparent. On the figures of drift rates referred to above, the drift is shown as a dotted line. NPM and NAA did not appear to use oscillators of sufficient stability, and drift rates could not be determined for these stations. Once the drift rates are known, corrections can be predicted and applied to the navigational calculations. To find the microseconds correction

correction = (predicted error)(H)(0.36)(10^{10}) where the correction is in microseconds and H is the time interval for the correction (usually the elapsed time since the previous fix). As an example, the predicted error for NBA on 21 January 1965 would be -1.0×10^{-10} and a correction to be applied to a 24 hour time period would be

$$\text{correction} = (1.0\times10^{-10})(24)(0.36)(10^{10}) = 8.65\ \mu\text{sec}$$

10. Great Circle Calculations.

The microseconds change recorded by a tracking receiver, when corrected and changed to distance, represents the shift in the position of the ship along the great circle between the ship and the transmitter. This change is applied along the great circle propagation path through the last known position of the ship. If a circle is then drawn through this corrected point, with the center of the circle at the transmitter site, the circle is then the line of position to be used for the new fix.

Charts can be overprinted with circles concentric to the VLF stations considered useful for the locality. Figure 15 is a portion of such a chart. In this case the circles are 33.4 miles (200 μsec) apart, with the distance to the station noted on each circle. When a new ships position is desired, the lines of position are easily found by drawing lines parallel to the circles at the appropriate distance from the last known position.

If overprinted charts are not available, the great circle bearing and distance to the transmitter can be found by computation. Methods for computing these values for the spherical earth can be found in books on navigation or radio wave propagation[1][9].

At the distance where the VLF signals are useful the concentric circles approximate straight lines for small areas. For this reason the line of position can be drawn as a straight line perpendicular to the computed great circle

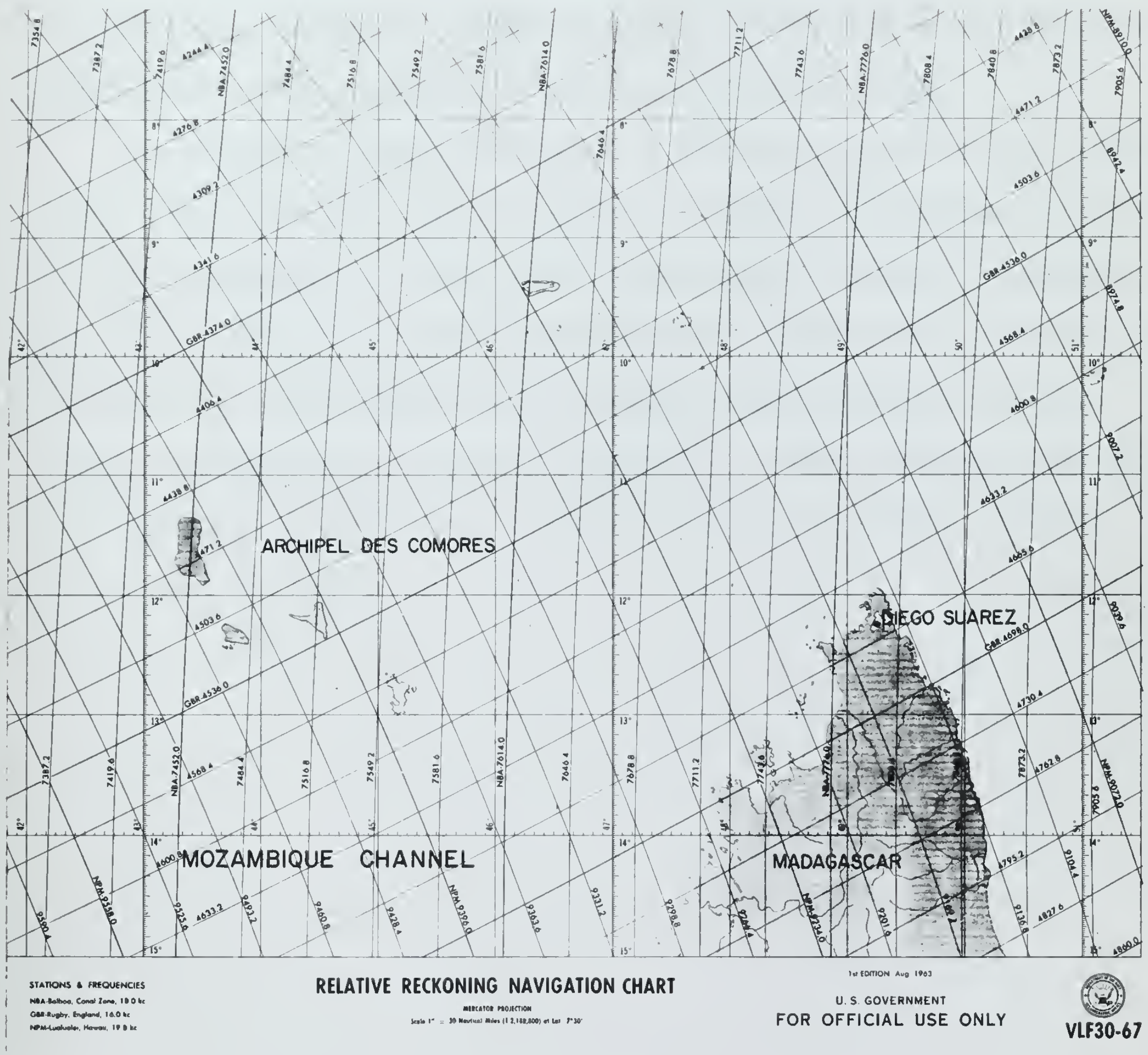


FIG. 15. A PORTION OF A CHART OVERPRINTED FOR VLF NAVIGATION

path. Unfortunately, this straight line approximation will deviate excessively from the actual concentric circle if the new position is more than about 50 miles from the computed great circle. In addition, errors may result from the spherical earth calculation since the earth is actually slightly elliptical. With this form of relative navigation such errors may accumulate over a period of days.

In order to keep errors at a minimum, many of the great circle calculations are necessary. These can become tedious if done manually. Luckily the high speed digital computer is well suited to these calculations. These calculations can be made for each degree of latitude and longitude and the values published in volumes similar to other tables used by navigators. Errors can be minimized by averaging between the given values.

11. The Ship Navigation Problem.

Many changes in a VLF signal that are apparent and easily corrected at a fixed receiver location are not so apparent on a moving ship and can result in large navigation errors. Examples of these are:

1. The transmitter leaves the air, either for a scheduled maintenance period or for some other reason.
2. Cycle-slipping occurs.
3. The transmitter master oscillator is corrected.
4. The transmitting frequency is changed.
5. Keying is changed from CW to FSK.

Corrections for the errors caused by these changes are possible, and methods of finding these corrections are described below.

The VLF stations used for navigation must leave the air occasionally for routine maintenance. During these periods the tracking receiver on the ship will stop tracking, and when the station resumes transmitting a few hours later the elapsed microseconds will not be correct. The transmitter master oscillator is not stopped during these maintenance periods of course, and when the transmitter comes back on the air the phase difference between the local oscillator and the received signal is exactly what it would have been if the transmitter had never been off. At a fixed receiver location these transmitter outages present no problem. Figure 16 shows an outage between 1330 and 1520 (simulated by disconnecting the antenna). On a ship the problem is more

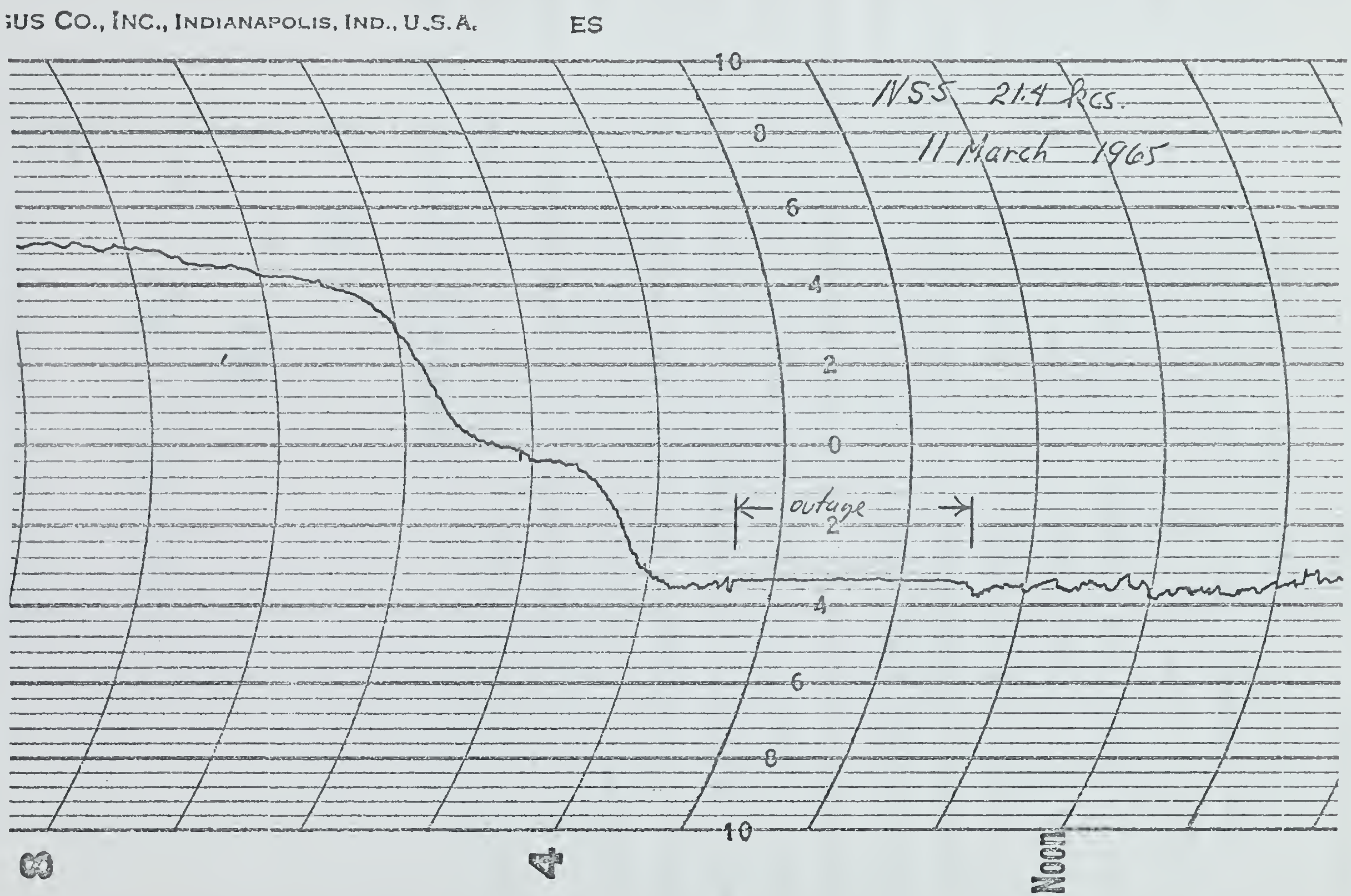


FIG. 16. A TRANSMITTER OUTAGE AS SHOWN ON THE PHASE PLOT (STATIONARY RECEIVER)

complex, since one or more full cycles may be lost during the outage because of the movement of the ship. Consequently when tracking is resumed the next line of position must be changed by a distance equivalent to some integral number of cycles. If the length of the outage is known, the number of cycles lost can be computed by dividing the distance the ship has traveled away or toward the transmitter by the length of one cycle. If the length of the outage is not known, or if the distance traveled cannot be determined, the corrected line of position is that corrected line that falls nearest the presumed position of the ship. If 3 or more stations are being tracked the corrected line of position would be the line that falls nearest the intersection of the two uncorrected lines (assuming that only one transmitter left the air since the last fix). Table VII is a listing of some wavelengths in microseconds, kilometers and nautical miles. Values for frequencies not listed in Table VII can be found by using the following equations:

$$t = \frac{1000}{f}$$

$$d\ (\text{miles}) = \frac{t}{6.82}$$

$$d\ (\text{km}) = \frac{t}{3.68} = d_{(\text{miles})}(1.852)$$

where

t = microseconds per wavelength

f = frequency in kilocycles per second.

[illegible]

Frequency	Wavelength		
f (kcs)	t (μsec)	D (naut. miles)	D (km)
16.0	62.5	9.16	16.97
17.8	56.3	8.25	15.27
18.6	53.8	7.86	14.55
19.8	50.5	7.40	13.70
20.0	50.0	7.33	13.57
21.4	46.75	6.84	12.65
24.0	41.7	6.11	11.31
26.1	38.3	5.61	10.40

TABLE VII

Wavelengths of Some Commonly Used Frequencies

Frequency	Wavelength		
f (kcs)	t (μsec)	D (naut. miles)	D (km)
16.0	62.5	9.16	16.97
17.8	56.3	8.25	15.27
18.6	53.8	7.86	14.55
19.8	50.5	7.40	13.70
20.0	50.0	7.33	13.57
21.4	46.75	6.84	12.65
24.0	41.7	6.11	11.31
26.1	38.3	5.61	10.40

TABLE VII

Wavelengths of Some Commonly Used Frequencies

Cycle-slipping is another possibility for error. This phenomenon may occur occasionally during the steeply rising and falling portions of the diurnal phase shift trapezoid. During these periods the diurnal phase shift may be larger than a half cycle and so rapid that the receiver does not track the proper cycle and slips a full cycle to the nearer but improper tracking point. Another cause for cycle-slipping may be phase interference between signals arriving by both great-circle paths or from multimodal interference during the transition from night to day or day to night[24]. Figure 17 shows cycle-slipping on the track of NPM (26.1 kcs) during sunrise at the U. S. Naval Postgraduate School. The dotted line shows the true track. Correction for cycle-slipping is similar to the correction for loss of signal since an integral number of cycles, normally only one, have been gained or lost. It may not be easy to spot cycle-slipping on a moving ship, so a correction may be required if the line of position seems in error by one or more cycles. Once again, the correction will be more obvious if many stations are being tracked.

Occasionally it may be necessary to readjust the transmitter master oscillator to bring it within tolerance. When this is done, the ships record will be in error by the number of microseconds equivalent to the change. If high quality oscillators are used at the transmitters, these changes should be infrequent. In addition they can be scheduled a few weeks in advance and ships using these sta-

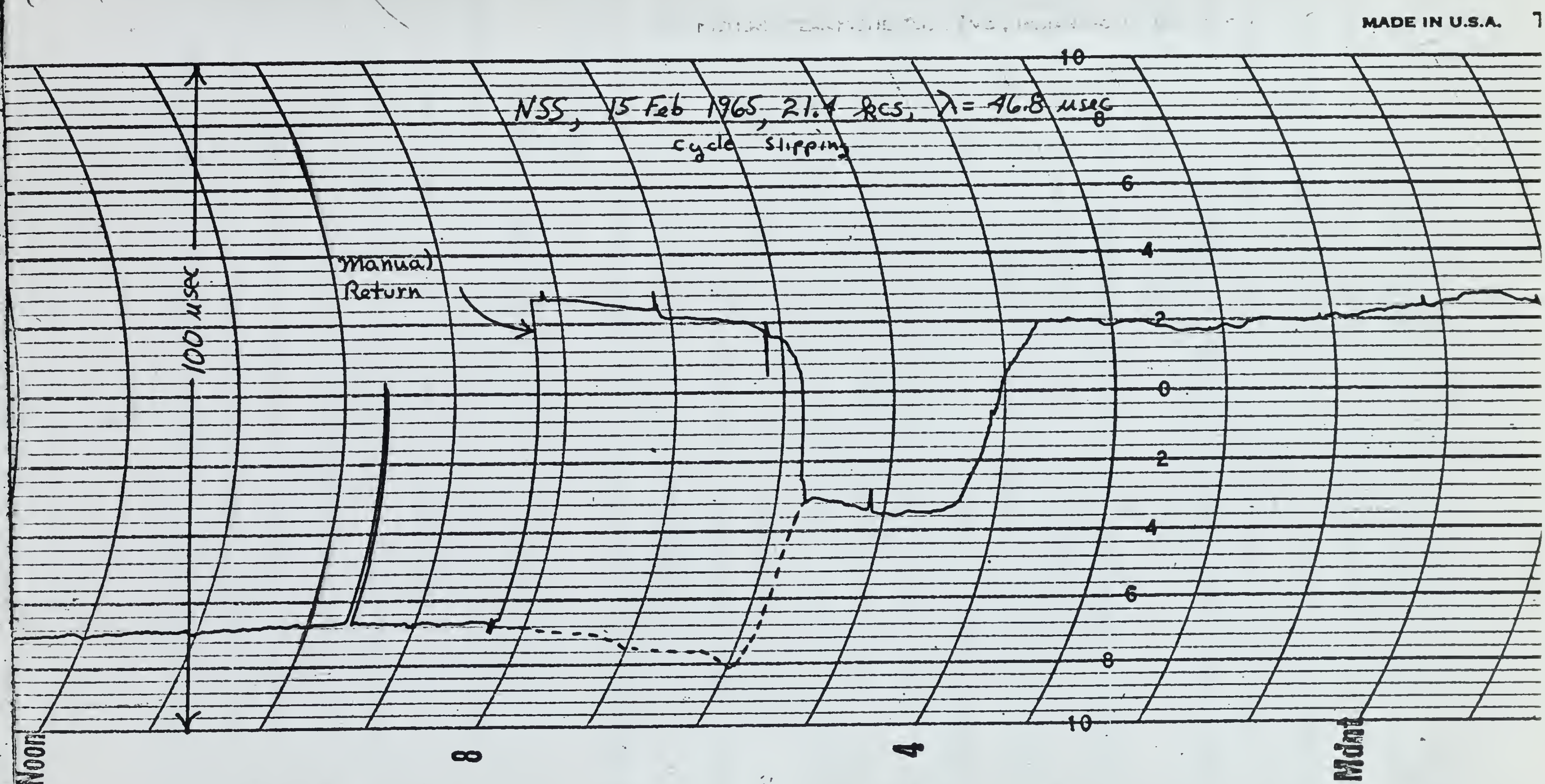


FIG. 17. AN EXAMPLE OF CYCLE-SLIPPING

tions for navigation may be notified by message. It might be possible to correct the line of position shortly after the change is made by adding or subtracting the microseconds equivalent, but more likely the correction will be made by forcing the line of position through the first fix after the oscillator adjustment. The oscillator drift rate will not be affected by this change.

The Navy operated transmitters may change frequency. This will be anticipated, and a notification of this change will be sent. Figure 18 is an example of such a notice. When a station is shifted in frequency its previous tracking history is of little use in finding a future line of position. A new fix must be found using other means, and tracking started from that fix. Since the stabilized oscillator at the transmitter is not altered when the frequency shift occurs, the drift rate at the new frequency should remain constant. When many stations shift frequency as in Figure 18, the new fix may have to be found by means other than VLF transmissions.

When the transmitted signal is shifted from CW to FSK type keying, it may or may not be usable for navigation. Measurements at the U. S. Naval Postgraduate School have indicated that NAA can not be tracked while transmitting FSK, while NPM can be used for navigation even when transmitting FSK, provided a 10 microsecond correction is added. The reason for this may be that NAA uses the wider frequency shift, or NPM may have one side of the frequency shift stabilized

U. S. NAVAL OBSERVATORY
WASHINGTON, D. C. 20390

TIME SERVICE ANNOUNCEMENT **21 May 1964**

Changes in the VLF Transmissions of NBA, NLK/NPG, and NAA

1. The frequency of NBA, Balboa, Canal Zone, will be changed from 18.0 kc/s to 24.0 kc/s on 8 June 1964.

2. The frequency of NLK/NPG, Jim Creek, Washington, will be changed from 24.0 kc/s to 18.6 kc/s on 1 June 1964.

3. The frequency of NAA, Cutler, Maine, will be changed to 17.8 kc/s with FSK when transmission is resumed on 5 June 1964, and will not be useable for frequency calibration.

4. The frequency of NSS, Annapolis, Maryland, continues on 21.4 kc/s.

T. S. BASKETT
Superintendent

FIG. 18. A FREQUENCY CHANGE NOTICE

to the precision frequency standard. If the use of VLF transmissions for navigation becomes common, all FSK transmissions will probably be made usable.

On a ship, the major problems in tracking VLF stations for navigation occur because the ship is moving, and most of the corrections necessary require a good fix. For this reason it will be useful to track as many VLF stations as possible in order to have a good fix available when there is some change in a transmission during the run between fixes. Another problem is the high frequencies presently used by most Navy transmitters. The lower frequencies are the most useful for navigation because there is less probability of an error on one cycle when a wavelength is long with respect to the possible accumulated errors. As indicated in Table VII, one cycle for NPM at 26.1 kcs. occurs every 5.61 miles, and this frequency could very likely be too high to be used.

An important feature of VLF navigation that must be recognized is that an error in a position will not correct itself at a subsequent fix. Once a ships position is found, the lines of position are carried forward from that point, and if this fix were in error this error would be carried on to the next fix with no change. Because of this, it will be necessary to periodically check the ship's position as found from VLF by other independent means.

One of the advantages of the VLF navigation system is the possibility of an automated, accurate, all weather navigation system using this scheme. It should be possible to

continuously plot the ships position on standard navigation charts. Although the instrumentation of such a system was not investigated, it does appear possible to construct such a device. Since corrections for most common sources of error are similar (searching through integral wavelengths for the proper line of position) a program to compensate for these can be developed. An operator would probably have to insert corrections for other possible errors, and the output of the system would have to be checked against a known position periodically to eliminate accumulated error.

A particularly useful application of the VLF navigation system is its use on nearly stationary ships, such as a ship on a semi-permanent ocean station. When used at a fixed location any errors contained in a received signal can easily be spotted and corrected. In addition, 24 hour navigation is possible since the previous days track of a VLF signal will provide accurate corrections for the diurnal phase shift during the following 24 hour period.

12. A Sample Problem.

Finding a ships position from the VLF transmission is not difficult, provided overprinted charts or tables of VLF bearings and distances are available. Figure 19 is an example of a page from such a table.

A typical problem is shown on a portion of a position plotting sheet in Figure 20. The ships position is known at 0800. This position could have been obtained from a star fix, Loran, or a previous VLF fix. The phase difference reading for the VLF stations of interest are also known. This information is obtained either by recording the microseconds dial reading on the VLF receiver at 0800, or by finding the readings at this time on the charts recording the output of the phase comparators. It is desired to fix the position of the ship at 1200. Table VIII shows the bearing and ranges for the VLF stations. These were obtained from tables similar to Figure 20. The values are for the integer latitude and longitude nearest the known ships position at 0800, in this case 128.0 W, 38.0 N. From Table VIII we that NLK, NPM, and WWVL are within the near zone of 4000 kilometers (2160 N miles), and signals from these stations will not be used.

It will be necessary to compute the expected diurnal phase shift for the remaining stations. The times of sunrise and sunset at each of the usable stations must be known, and transferred to local time. These values may be available from previous computed tables, or they can be computed on

TRANSMITTER STATION-GBR

RECEIVER POSITION LAT	LONG	BEARING	DISTANCE (NMILES)	(KM)
10.00	129.00	29.72	6208.58	11498.30
11.00	129.00	29.60	6156.73	11402.27
12.00	129.00	29.50	6104.82	11306.13
13.00	129.00	29.40	6052.85	11209.88
14.00	129.00	29.31	6000.83	11113.54
15.00	129.00	29.23	5948.76	11017.11
16.00	129.00	29.16	5896.65	10920.60
17.00	129.00	29.09	5844.50	10824.01
18.00	129.00	29.03	5792.31	10727.36
19.00	129.00	28.98	5740.09	10630.64
20.00	129.00	28.94	5687.83	10533.87
21.00	129.00	28.90	5635.56	10437.05
22.00	129.00	28.88	5583.26	10340.19
23.00	129.00	28.86	5530.94	10243.29
24.00	129.00	28.84	5478.60	10146.37
25.00	129.00	28.84	5426.25	10049.42
26.00	129.00	28.84	5373.90	9952.46
27.00	129.00	28.85	5321.54	9855.48
28.00	129.00	28.86	5269.17	9758.51
29.00	129.00	28.89	5216.81	9661.54
30.00	129.00	28.92	5164.46	9564.57
31.00	129.00	28.96	5112.11	9467.63
32.00	129.00	29.00	5059.78	9370.71
33.00	129.00	29.06	5007.46	9273.82
34.00	129.00	29.12	4955.16	9176.96
35.00	129.00	29.19	4902.89	9080.16
36.00	129.00	29.26	4850.65	8983.40
37.00	129.00	29.35	4798.44	8886.70
38.00	129.00	29.44	4746.26	8790.07
39.00	129.00	29.54	4694.12	8693.51
40.00	129.00	29.65	4642.03	8597.04
41.00	129.00	29.77	4589.99	8500.66
42.00	129.00	29.89	4538.00	8404.37
43.00	129.00	30.02	4486.07	8308.19
44.00	129.00	30.17	4434.20	8212.13
45.00	129.00	30.32	4382.40	8116.20
46.00	129.00	30.48	4330.67	8020.40
47.00	129.00	30.65	4279.02	7924.74
48.00	129.00	30.83	4227.45	7829.24
49.00	129.00	31.02	4175.97	7733.90
50.00	129.00	31.22	4124.59	7638.74
51.00	129.00	31.43	4073.31	7543.77
52.00	129.00	31.64	4022.14	7449.00
53.00	129.00	31.87	3971.08	7354.44
54.00	129.00	32.12	3920.14	7260.10
55.00	129.00	32.37	3869.33	7166.00
56.00	129.00	32.63	3818.66	7072.16
57.00	129.00	32.91	3768.13	6978.58
58.00	129.00	33.20	3717.75	6885.28
59.00	129.00	33.50	3667.54	6792.28
60.00	129.00	33.81	3617.49	6699.59

FIG. 19. A PAGE FROM A TABLE OF GREAT CIRCLE RANGES AND BEARINGS

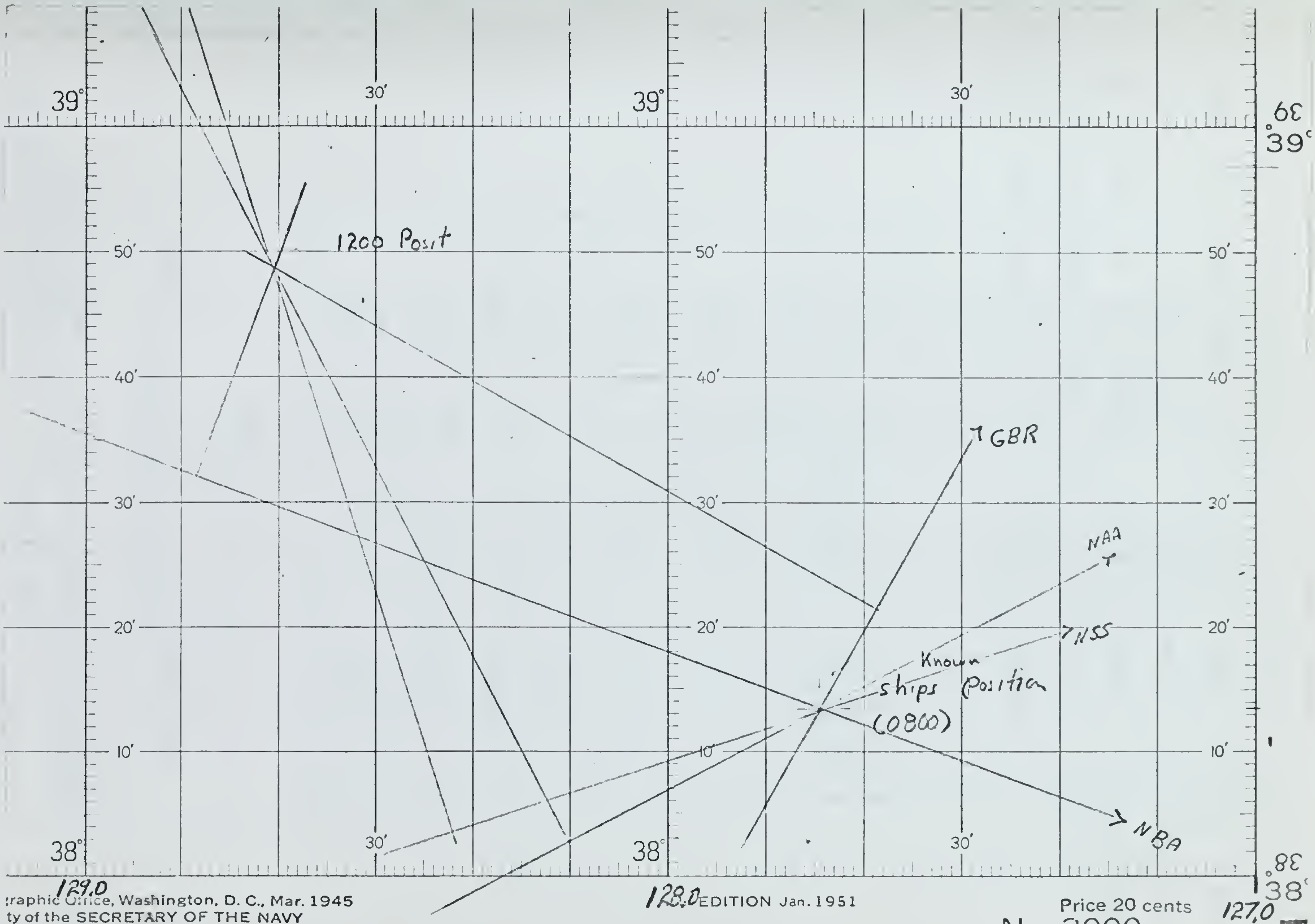


FIG. 20. A SAMPLE PROBLEM

board ship. The times of sunrise and sunset locally must be calculated. The times of sunrise and sunset calculated and listed in the tables are not those at sea level, but those at an altitude of 70 kilometers where the lower reflecting layer of the ionosphere forms. Values of k_V for the local area must also be known so the Δt may be calculated.

Station	Bearing (degrees)	Distance (N miles)
NLK	21.48	666.69
NPM	246.04	1847.41
NSS	71.98	2394.26
NAA	61.31	2708.03
NBA	110.70	3129.80
GBR	30.02	4670.90
WWVL	74.19	1076.47

TABLE VIII

Bearing and Distance of VLF Stations from 128.0W, 38.0 N

Table IX shows the times of sunrise and sunset for the desired VLF stations for a typical day.

VLF Station	GMT Sunrise	Sunset
NBA	1052	2351
NSS	1035	2343
NAA	0956	2307
GBR	0528	1846

TABLE IX

Times of Sunrise and Sunset for a Typical Day

Local sunrise and sunset are computed, corrected for altitude and found to be 0528 and 1836 respectively, local time. The tabulated values of sunrise and sunset from Table IX are corrected to local time by adding the time equivalent of the differences in longitude.

128.0W Longitude = 8hr. 32 min.

local times of sunrise and sunset for the VLF stations

	sunrise	sunset
NBA	0220	1519
NSS	0203	1511
NAA	0124	1435
GBR	2056	1014

Values of k_v are found from Table II for NSS, NBA, and GBR. The value of Δt is found from this and the values of distances in Table VII, $\Delta t = (k_v D)(1.86)$.

VLF Station	Freq (kcs)	k_v $(x10^3)$	Δt (μsec)
NBA	24.0	8.20	47.7
NSS	21.4	7.65	34.0
NAA	17.8	7.22	36.4
GBR	16.0	7.28	63.3

The values of k_v used are the best available and will serve as examples.

From the values found for sunrise, sunset and Δt, the trapezoidal pattern expected for the diurnal shift can be constructed. These are shown in Figure 21.

From Figure 21 it is clearly seen that during the period 0800-1200 local time, the propagation paths for NBA, NSS and NAA are completely in daylight and no correction for diurnal shift is necessary for these stations. The GBR propagation path is in daylight at 0800 but is partially in the dark at 1200. The correction to the microseconds reading at 1200 can be found from Figure 21, and is 13 microseconds.

The final correction to the microseconds difference reading is that correction for drift rate. These rates are obtained as explained in section 9 from graphs similar to Figures 13, 14, 15 and 16. Some typical drift rates might be as follows, where drift rate is in microseconds per 24 hours.

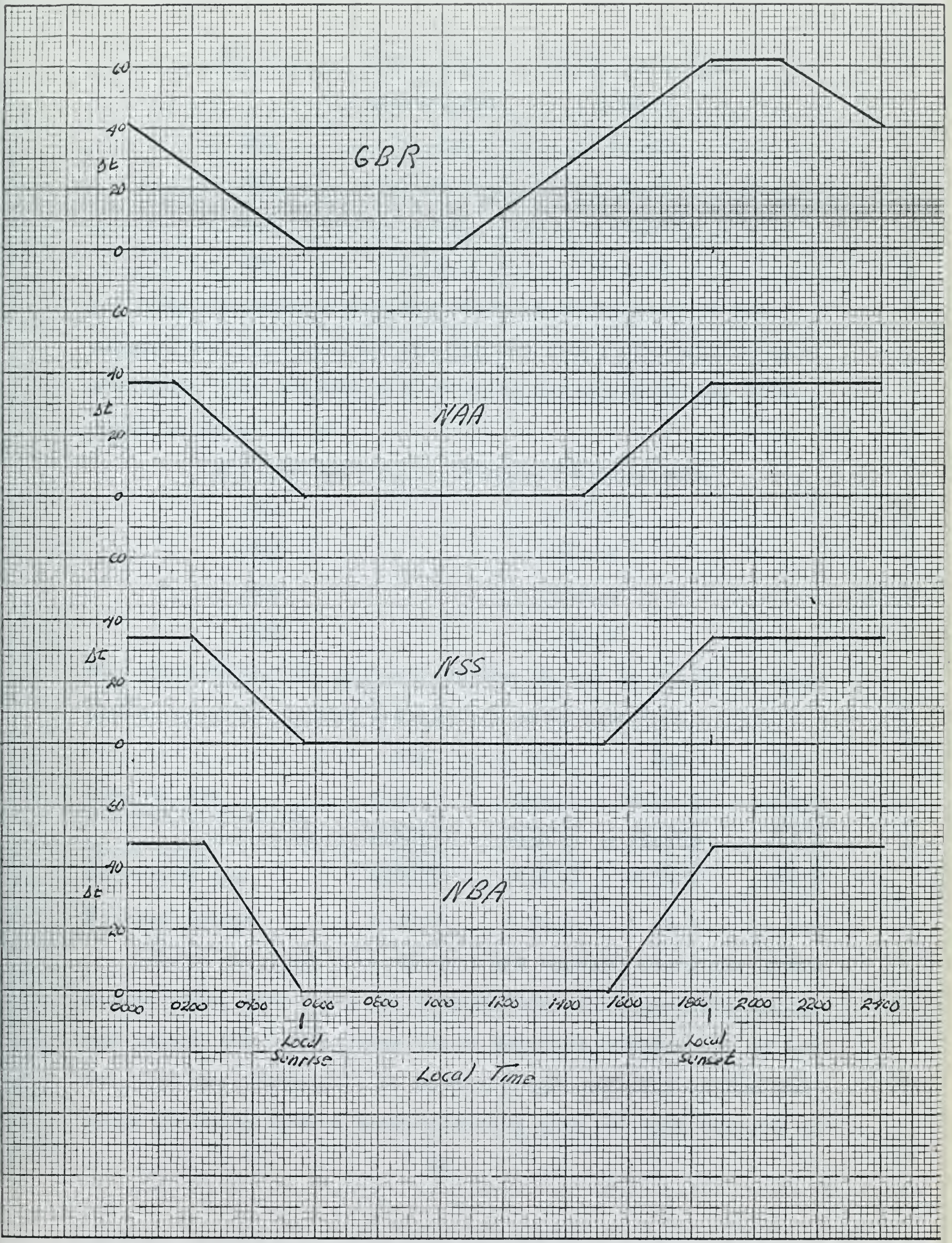


FIG. 21. CONSTRUCTED TRAPEZOIDAL DIURNAL SHIFT PATTERNS

Station	Drift Rate (μsec/24hr)	Drift in 4 Hour (μsec)
NBA	-10	-1.67
NSS	-8	-1.33
NAA	-10	-1.67
GBR	-9	-1.50

The corrections are now ready to be applied to the elapsed microseconds and the various lines of position constructed. The elapsed microseconds between 0800 and 1200 might be found to be

VLF Station	Elapsed Microseconds
NBA	+334.7
NSS	+194.1
NAA	+143.8
GBR	- 64.6

The corrections are applied and the change in ships position along the great circle propagation path computed.

	NBA	NSS	NAA	GBR
Elapsed sec	+334.7	+194.1	+143.8	-64.6
Diurnal correction	0	0	0	+13.0
	+334.7	+194.1	+143.8	-51.6
Drift rate	-1.7	-1.3	-1.7	-1.5
Corrected sec	+333.0	+192.8	+142.1	-53.1
N Miles Change	+ 53.8	+ 31.2	+ 23.0	- 9.4

These nautical mile changes are applied along the great circle path, away from the transmitter for a positive change and toward the transmitter for a negative change. It is useful, but not essential, to have a rough estimate of the new ships position from a dead-reckoning plot so that changes in

the great circle bearings can be averaged to reduce error. In this sample problem the new ships position is known to be near 129.0W, 39.0N, and the great circle ranges and bearings are obtained from the tabulated values. These are listed in Table X. Comparing these values with those in Table VIII it is seen that there is little difference in bearing for those stations beyond 4000 kilometers. The difference in bearing caused by averaging will certainly be less than the construction error on Figure 20. These averages are found however and are:

Station	Average Great Circle Bearing
NBA	110.64
NSS	72.32
NAA	61.62
GBR	29.78

These bearings are plotted and the computed changes in miles are measured along these lines in the proper direction. The lines of position are then drawn perpendicular to the great circle lines at this point. The intersection of these lines of position results in a fix, as shown in Figure 20.

Station	Bearing (degrees)	Distance (N miles)
NLK	26.74	631.30
NPM	243.32	1830.30
NSS	72.77	2420.99
NAA	61.93	2721.01
NBA	110.58	3194.86
GBR	29.54	4694.12
WWVL	77.12	1107.28

TABLE X

Bearing and Distance of VLF Stations
from 129.0W, 39.0N

The procedure for finding the ships position in an area where overprinted charts are available is similar except that tables of bearing and distance to the VLF stations are not necessary. This information is contained on the chart in the form of lines of equal distance from the stations. The nautical miles change is computed as before, and this change is measured along a line through the last ships position perpendicular to the lines of equal distance for the VLF station. The line of position is then a line parallel to these lines of equal distance.

13. Comparison With Other Electronic Navigation Systems.

It appears pertinent to examine how the VLF navigation system of this paper compares generally with other electronic navigation systems. Some other systems presently in use are LORAN A, LORAN C, DECCA and Radux-Omega.

LORAN A operates at frequencies near 2 megacycles and is useful at ranges out to about 650 nautical miles during daylight and about twice that at night. It is a pulsed system utilizing a master and a slave station. A special receiver measures the difference between the time of arrival at the ship of the pulses from the master and slave signals. Special charts are published, giving lines of constant time difference for each pair of stations within range. The position of the ship is found at the intersection of the time difference lines. Many pairs of stations are required to cover an ocean area because of the relatively short useful range of the transmitted signal. Propagation inconsistencies can cause large errors at distances where reception of the pulses is marginal.

LORAN C is also a pulsed system, but operates at about 100 kcs., and consequently has longer range with more stable propagation conditions. In addition more accurate comparison of the two received pulses is possible since the LORAN C receiver compares the time between separate and corresponding oscillations of the master and slave stations. This is called cycle-matching. As with LORAN A, a fix is found at the intersection of time difference lines on special LORAN C

charts. LORAN C is considered useful up to a 2000 mile range with good accuracy.

The DECCA system also operates at low frequency, but does not use pulses. In this system a master station is surrounded by three slave stations at distances of 60 to 120 nautical miles. These stations operate at frequencies that are all different, but are all harmonics of some lower fundamental frequency. The transmitter frequencies may lie in the range of 70 to 120 kcs. The four transmitters broadcast a continuous wave, with all slave stations related in phase to the master station. Special equipment aboard the ship compares the phase between the four stations and gives an output on special recorders, called decometers. A fix is obtained by transferring the decometer readings to special charts with lines corresponding to various readings. A ships position is found at the intersection of the indicated lines. In spite of the low operating frequency, this is considered to be a short range system, with a maximum range of 240 nautical miles. Accuracy varies from less than one quarter mile during full daylight at close range to 8 miles during dusk at maximum range(11).

The Radux-Omega navigation system operates at VLF frequencies, and is a long range system using phase comparison between signals transmitted by a master and a slave station. The slave station is phase locked to the signal transmitted by the master station. The master and slave stations transmit alternately on the same frequency, and equipment on the

ship measures the phase difference between the two received signals. Phase ambiguities occur in lanes separated by one-half the wavelength of the operating frequency. Lane identification is accomplished by alternate transmission by both master and slave on two frequencies. A ships position is obtained at the crossing point of lines of equal phase difference. Charts are printed containing the lines of equal phase difference for each pair of stations. Ranges in excess of 5000 nautical miles are expected, and a network of eight stations can provide 15 sets of lines of position by phase relations between the various stations(12).

The method of navigation discussed in this paper differs from the systems previously discussed. This system can be used, for example, without specially prepared charts by utilizing tables of previously computed great circle calculations. In addition, the shore stations utilized are presently in operation for purposes of communications. As with Radux-Omega the received signal must be corrected for changes along the propagation path, but in this system the correction can be found from the previous days record. A disadvantage is the lane identification problem, but this can be simplified by utilizing lower operating frequencies to widen the lanes, and by using as many stations as possible for obtaining the fix. The lane identification problem can be further simplified by using other methods of navigation to find the ships position within a half lane width. The shipboard equipment necessary for this system is also simple when

compared to the equipment necessary for most existing systems.

The accuracy of this system should be close to that predicted for the Omega system[12]. In the Omega system, a 24 hour RMS accuracy of 0.5 mile during the day and 1.2 miles at night is predicted. For 24 hour use of the Omega system, tables of corrections for the diurnal phase shift must be available.

The method of navigation discussed in this paper may not be usable by Naval ships that change course often and spend long periods at sea. In its present form is should be particularly useful for ships that desire to remain at a fixed ocean station or by oceanographic vessels.

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14. Comments and Recommendations.

The primary test of a navigation system is how well a ships navigator can use it for navigation. Most of the data used in this paper were obtained at the U. S. Naval Postgraduate School at Monterey, California. It is not difficult to navigate a building, which is one way to say the author was not able to test the system properly. As a consequence, before any consideration can be given to the value of this system, considerable testing under shipboard conditions will be necessary. For instance, how does the roll and pitch of a ship using a vertical antenna for reception effect the reception of a VLF signal of very low signal strength. This testing seems appropriate and is recommended.

The data on drift rates which is plotted as Figures 11, 12, 13 and 14 was obtained using a Rubidium Vapor Frequency standard, as noted in Chapter 7. The spread in data points, although generally within the frequency tolerance of the VLF stations, was greater than expected. It may be that some of the spread was caused by the local standard and because of this a good crystal oscillator would be preferred for navigation purposes. A crystal oscillator of sufficient stability was not available during periods data was taken. When such an oscillator is available similar data should be taken using the crystal as the primary standard. If possible both the crystal oscillator and the rubidium standard should be used to obtain drift rates simultaneously. Two tracking receivers will be necessary for this procedure.

The author had hoped to compare antennas used for the VLF tracking receiver. The antenna used was a Textran loop, oriented to receive signals from the North-East. A loop is not satisfactory for use on a ship and a comparison between the loop and a good quality whip would be useful when a whip becomes available. Unfortunately the noise level at the antenna location used at the U. S. Naval Postgraduate School is high, and a whip may not be usable there.

It was concluded that signals within the multi-mode zone were not usable because of the interaction between modes. This is unfortunate since the VLF signals are of high signal strength in this zone. In particular, if VLF signals were usable for navigation in the multi-mode zone, transmitters with low radiated power could be established for navigation use. Since efficient antenna systems are the major expense of a VLF transmitting station, many low power transmitters with inefficient antennas can be established at relatively low cost. Reception at these low level signals is not difficult with the narrow bandwidth tracking receiver. A transmitter radiating 10 watts at a frequency of 15 kilocycles should be useful for navigation at ranges in excess of 2000 miles, and 1 watt of radiated power may be used at distances beyond 1000 miles. Even 0.1 watt might be useful at considerable distances. Of course it may be difficult to receive signals of such low levels unless they are known to be present at the exact frequency. The multi-mode zone should be investigated to determine how it might be used for navi-

gation, possibly with such low level signals.

Another aspect of this VLF navigation system that is deserving of further investigation is the development of an automated navigation system using VLF phase comparison. This method seems particularly adaptable to automatic plotting since phase variations transfer linearly to distance changes. Other VLF and LF systems, as noted in Chapter 13, use phase comparisons between master and slave stations, and consequently the lines of equal phase difference are hyperbolas.

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